ESSAYS ON ENVIRONMENTALLY RESPONSIBLE OPERATIONS

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ESSAYS ON ENVIRONMENTALLY RESPONSIBLE OPERATIONS

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SUMMARY

Focusing on issues that have not been fully explored in the sustainable operations and supply chain management literature, this dissertation comprises three essays covering two issues: the impact of public information dissemination regarding chemical hazards on reductions in chemical emissions, and the implications of secondary markets on durable-goods producers' warranty-length decisions. The first essay (Chapter 2) empirically examines the association between changes in hazardous substance rankings and the voluntary reductions in their emissions at the facility level, as well as the extent of efforts including the use of source reduction and end-of-pipe treatment. The study also examines how these relationships are moderated by operational leanness. The results suggest that the public information dissemination of chemical rankings—the relative hazard level of chemicals—is effective to promote environmental actions, as indicated by the significant association between increases in the relative assessed hazard levels of chemicals and greater subsequent reductions in emissions and the use of source reduction. In addition, the study also finds that operational leanness may limit the ability of facilities to reduce emissions in response to increases in relative assessed hazard levels. The second essay (Chapter 3) analytically examines durable-goods producers' warranty-length decisions in the presence of secondary markets and how producers' secondary market interference influences their decisions. The study finds that with respect to the reliability of used products, the benefit of offering longer warranties is non-monotonic when a secondary market is present. It also shows that secondary market interference significantly influences producers' warranty-length decisions. In addition to the conventional wisdom that producers benefit from offering longer warranties when product reliability is a concern, producers engaging in secondary market interference may find that offering longer warranties is more profitable when their used products are sufficiently reliable. The third essay (Chapter 4) then empirically examines predictions drawn from the analytical findings in the US automobile market. The results show support for a U-shaped relationship between automobile producers' warranty lengths and their used-vehicle reliability. Specifically, automobile producers offer longer non-power-train related warranties when the reliability of their used vehicles is near an extreme, either low or high. This study also documents the relationship between the extent of producers' buy-back activities and their used-vehicle reliability, and that between secondary market trade volume and used-vehicle reliability. Both are in line with the analytical findings.

CHAPTER 1

INTRODUCTION

Motivated by personal experience interacting with operations managers in the field, this dissertation examines issues that have not been fully explored in the sustainable operations and supply chain management literature, including the impact of public information dissemination regarding chemical hazards on reductions in chemical emissions and the implications of secondary markets on durable-goods producers' warranty-length decisions. This dissertation comprises three essays relating to these two issues: the first essay empirically examines the association between changes in hazardous substance rankings and the voluntary reductions in their emissions at the facility level; the second essay uses a normative model, focuses on the profitability of a durable-goods producer's warranty-length decision, and investigates the implications of the presence of a secondary market and the impact of the producer's secondary market interference on the decision; the third essay draws predictions from the analytical findings in the previous essay and empirically tests them using data from the US automobile market.

The public dissemination of information about the hazards of chemicals can be expected to lead to pressure on facilities or firms to undertake voluntary environmental actions. While the US Agency for Toxic Substances and Disease Registry (ATSDR) provides extensive public information about the potential hazards of a wide range of industrial chemicals and ranks chemicals by their relative assessed hazard level, limited empirical research has been devoted to examining (i) the link between such informational approaches and firms' voluntary environmental efforts, and (ii) the implications of firms operational characteristics on the extent and the nature of these efforts. In the first essay, titled "Are Hazardous Substance Rankings Effective? An Empirical Investigation of Changing Assessments of the Relative Hazards of Chemicals and Voluntary Emissions Reductions" (Chapter

2), we enhance the understanding of these issues by empirically investigating facility-level voluntary reductions in emissions and the nature of efforts (i.e., the use of source reduction and end-of-pipe treatment) in relation to changes in chemical ranks—the relative assessed hazard levels of the chemicals. We also examine the moderating effects of operational leanness, an attribute that previous studies have found to be associated with better environmental performance, on these relationships. To test our hypotheses, we draw data from four secondary data sources: the Substance Priority List from the ATSDR, the Toxics Release Inventory from the EPA, the National Establishment Time-Series, and Compustat, and employ a two-way fixed-effects panel model to control for various facility and industry factors.

Through this study, we demonstrate that increases in relative assessed hazard levels are associated with greater reductions in emissions and increased use of source reduction, suggesting that information dissemination is effective to promote environmental actions. In other words, we find evidence that managers may recognize changes in the relative assessed hazard level of chemicals, internalize associated risks, and undertake voluntary actions accordingly. We also find evidence that operational leanness, which aims to eliminate waste and reduce variability, may limit the ability of facilities to reduce emissions in response to increases in the relative assessed hazard level. These new insights will help operations and environmental managers fine-tune their expectations about the impact of adopting lean practices. Furthermore, we highlight the implications of facility and industry characteristics on the effectiveness of such information dissemination.

In the second essay, titled "Product Warranty Lengths and Secondary Market Interference" (Chapter 3), we examine producers' decisions regarding their product warranty lengths in durable-goods markets. The motivation for this study came from discussions with aftermarket operations managers concerning the implications of product warranties on the secondary market for their products. After a thorough review of the literature, we realize that the impact of warranties in the presence of secondary markets has not been fully examined. We therefore set out to explore the implications of product warranties in durable-goods markets where secondary markets typically prevail.

To this end, we developed a durable-goods market model that focuses on benefits from warranty coverage in the context of a product that is reliable to an extent and incorporates a producer's incentives to interfere with the secondary market (specifically through buy-backs). Analysis of this model formulation under three different scenarios: (i) without a secondary market, (ii) with a secondary market but no secondary market interference, and (iii) with secondary market interference, has allowed us to characterize conditions under which offering longer product warranties is more profitable, and to explore the implications of the presence of the secondary market and the impact of the producer's secondary market interference. This analysis helped identify surprising insights: in the presence of a secondary market, the warranty-length decision is non-monotonic with respect to used-product reliability; secondary market interference through a buy-back program significantly influences the warranty-length decision. In addition to the conventional wisdom that producers benefit from offering longer warranties when product reliability is a concern, we find that durable-goods producers engaging in secondary market interference may find that it is more profitable to offer longer warranties when their used products are sufficiently reliable.

In the third essay, titled "Empirical Tests of Product Reliability on Product Warranty Lengths and Secondary Markets" (Chapter 4), we draw predictions from the analytical findings and empirically test them in the US automobile market. In this study, we link secondary data from the Consumer Expenditure Survey by the US Bureau of Labor Statistics, the Vehicle Dependability Study from J. D. Power, and the detailed warranty coverage information collected by JL Warranty. We apply the exploratory factor analysis to identify key factors in automobile producers' warranties and deploy panel-data models to control for various factors. The results show support for a U-shaped relationship between automobile producers' warranty lengths and their used-vehicle reliability. Specifically, automobile producers offer longer non-power-train related warranties when the reliability of their used vehicles is near an extreme, either low or high. The study further shows that the association between the extent of producers' buy-back activities and their used-vehicle reliability is negative, and that the relationship between trade volume in the secondary market and used-vehicle reliability is positive. Both are in line with the analytical predictions.

The studies in the second and third essays together offer a compelling explanation to durable-goods producers' decisions on the length of product warranties with respect to product reliability. Offering longer warranties can be profitable when the reliability of used products and the engagement of secondary market interference are properly aligned. Durable-goods producers should evaluate their warranty-length decisions jointly with their decisions on secondary market interference.

CHAPTER 2

ARE HAZARDOUS SUBSTANCE RANKINGS EFFECTIVE? AN EMPIRICAL INVESTIGATION OF CHANGING ASSESSMENTS OF THE RELATIVE HAZARDS OF CHEMICALS AND VOLUNTARY EMISSIONS REDUCTIONS

2.1 Introduction

Enacting environmental legislation, such as limits on emissions, requires detailed cost and benefit assessments, involves many players, typically proceeds in a long-drawn fashion, and, thus, has an uncertain outcome (Beavis & Dobbs 1986, Hartl 1992, Batabyal 1995, Drake & Just 2016). In contrast, despite not directly regulating the behavior of facilities or firms, information-based regulatory approaches—such as the *dissemination of information* on the potential hazards of chemicals or the requirement of *disclosure of emissions* of certain chemicals (e.g., as is required under the United States Environmental Protection Agencys (US EPAs) Toxics Release Inventory (TRI) Program)—result in public awareness of chemical hazards and the environmental implications of facilities or firms operations. This awareness can be expected to lead to public pressure on facilities or firms to internalize the risks revealed by the information.

An example of the public dissemination of information on chemicals is the Substance Priority List (SPL), published by the Agency for Toxic Substances and Disease Registry (ATSDR). Established under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980, commonly known as the Superfund Act, ATSDR is the main source of information about the health effects of exposure to hazardous chemicals and is responsible for maintaining toxicological databases and disseminating information to other governmental agencies and public health professionals (ATSDR 2009, 2012). ATSDR gathers information on the hazards of chemical substances, ranks chemicals in the SPL based on toxicity, frequency of occurrence at polluted sites, and probability of human exposure, and biennially publishes a list of the top 275 chemicals. The agency prioritizes these chemicals for continuing toxicological research efforts and the compilation and dissemination of their toxicological profiles to the public (ATSDR 1994a, 1994b, 2014). Changes in the ranks of chemicals in the SPL are often referenced in industry news outlets and publications (Keiser 2003, Pearl 2008, Paul *et al.* 2015).

Another example of the public dissemination of information by a governmental agency, albeit less exhaustive, is the National Toxicology Program (NTP), which publishes the Report on Carcinogens (RoC). This report identifies chemical substances that are known to or are anticipated to cause cancer in humans. In addition to governmental agencies, non-governmental organizations also disseminate information on chemical hazards; examples include the SIN (Substitute It Now!) List (International Chemical Secretariat 2014) and the Dirty Laundry Report (Greenpeace 2011).

The toxicological information prepared by ATSDR is referenced in various regulatory programs, including the TRI program. In addition, ATSDR also assists other agencies in determining future regulations pertaining to chemical substances (ATSDR 2009). For example, in 2002, the agency recommended pentachlorophenol—a hazardous chemical ranked 43 in the 2001 SPL as a candidate for the RoC (NTP 2002, 2012). Subsequently, the substance became a new member in the RoC in 2014 (NTP 2014) and firms have since been required to warn employees about their exposure to the chemical (US OSHA Regulation 29 CFR Part 1910.1200(d)(4)).

As an outcome of progress in toxicological research, the relative assessed hazard levels of chemicals—reflected in the form of their ranks in the SPL—are dynamic. For example, environmental studies have reflected growing concerns about the use of trichlorobenzenes (TCBs), which are commonly used as dye carriers in polyester dyeing processes (World Health Organization 2004). The SPL rank of one of its variants, 1, 2, 3-TCB, advanced from 334 in 1992 to 137 in 2015. Concurrently, in addition to implementing new technologies to reduce the use of water and chemicals in its dyeing processes, Nike encouraged its suppliers to specifically phase out TCBs from their manufacturing processes (Nike Inc. 2016, Zero Discharge of Hazardous Chemicals 2016). Another example is glycol ethers, a group of ether-based solvents and cleaning agents that are widely used in industrial cleaning. As the rank of glycol ethers in the SPL advanced from 575 in 1992 to 319 in 2015, the use of these solvents attracted considerable media attention, and industrial cleaning firms have been actively seeking a substitute (Quaker Chemical Corp 2015, Substitution Support Portal 2015c,b,a). The above anecdotal evidence may suggest that firms acknowledge the assessments of chemical hazards and undertake voluntary environmental actions in response. Moreover, studies in the environmental management literature suggest that emissions reductions efforts, driven by the management of business risk, should reflect the hazards of chemicals released by a firms facilities (Reinhardt 1999, Kleindorfer & Saad 2005). When a chemical is found to potentially cause greater harm as compared to other chemicals, firms can expect higher future costs for environmental compliance and consumer and occupational liabilities related to that chemical (Kraft *et al.* 2013). Thus, when the relative assessed hazard level of a particular chemical substance increases (reflected as upward movement in the SPL), firms can be expected to be more likely to prioritize voluntary reductions of emissions of that chemical. On the other hand, it is also possible that firms may not voluntarily or proactively respond to information such as in the SPL and may wait for the enactment of regulations before taking action.

Although governmental organizations such as ATSDR provide periodically-updated public information about the potential hazards of specific chemicals, limited empirical research has been devoted to examining: (1) the link between such information and the voluntary environmental efforts of facilities that use these chemicals, and (2) the implications of the operational characteristics of the facilities on the extent and nature of these efforts. We add to the understanding of these relationships by investigating voluntary reductions in chemical emissions in relation to changes in the relative assessed hazard levels of the chemicals, as evidenced in the periodically-updated SPL published by ATSDR. To capture voluntary reductions of chemical emissions, we use data from the TRI. The TRI Program mandates facility-level reporting and public disclosure of emissions of over 650 chemicals. Since the establishment of the program, the amount of reported emissions in the manufacturing sector has declined by more than half (EPA 2014). TRI data has been extensively used in the literature to examine voluntary environmental actions (e.g. Hart & Ahuja 1996, Klassen & Whybark 1999, King & Lenox 2001, 2002, Toffel & Marshall 2004, Doshi *et al.* 2013).

Within efforts to reduce chemical emissions, the two broad categories of practices employed are source reduction and end-of-pipe (EOP) treatment. Source reduction (also referred to as pollution prevention), which includes changing product designs and modifying production processes to *avoid* pollution, has been recommended as a way to achieve better environmental performance, gain competitive advantages, promote innovation, and improve financial performance (Klassen & Whybark 1999, King & Lenox 2002). On the other hand, EOP treatment (also referred to as pollution control) includes the use of equipment or methods to recycle, burn, or neutralize (i.e., *treat*) pollutants. While EOP treatment is typically not regarded to be as strategically valuable as source reduction, it requires no modifications to existing product designs and has a limited disruptive effect on production processes (Klassen & Whybark 1999, Dutt & King 2014). Both categories of practices are prevalent, and many studies have examined the implications of effort levels within the two categories in various contexts (Hart & Ahuja 1996, Klassen & Whybark 1999, King & Lenox 2002, Kroes *et al.* 2012). We contribute to this literature stream by investigating the nature of facilities emission reduction efforts when the relative assessed hazard levels of chemicals change over time.

Perhaps the most significant operations management practice pertinent to proactive environmental actions, or actions beyond regulatory compliance, is lean operations. Broadly defined, lean operations is a principle that aims to eliminate waste and reduce variability

(Hopp & Spearman 2004, Shah & Ward 2007). The phrase lean is green has emerged due to the rationale that, because of the focus on waste (including emissions), leaner facilities or firms can be expected to achieve better financial performance, as well as better environmental performance (King & Lenox 2001, Kleindorfer *et al.* 2005, Corbett & Klassen 2006). However, certain studies have empirically shown in various contexts that operational leanness might be disadvantageous in a dynamic environment (Rothenberg *et al.* 2001, Kleindorfer & Saad 2005, Azadegan *et al.* 2013, Eroglu & Hofer 2014). Specifically, when the business environment is more competitive or faces greater uncertainty, facilities or firms with more closely integrated operations with less slack are less flexible to adapt than those that allow operational buffers. We therefore examine how operational leanness *moderates* the relationship between changes in the relative assessed hazard levels of chemicals and facilities voluntary reductions in emissions of the chemicals, as well as their use of source reduction and EOP treatment for the chemicals.

To summarize, we investigate facilities reductions in chemical emissions and their use of source reduction and EOP treatment in relation to changes in the relative assessed hazard levels of the chemicals, as evidenced in their SPL ranks over time. In addition, we examine the moderating effects of operational leanness on these relationships. To test our hypotheses, we draw secondary data from four sources—the SPL from the ATSDR, the TRI from the US EPA, the National Establishment Time-Series, and Compustat. We employ a panel model with facility-chemical- and time-fixed effects and control for various facility and industry factors. We find that public information dissemination on the relative hazards of chemicals is effective, as indicated by the significant association between increases in the relative assessed hazard levels of chemicals and greater subsequent emissions reductions as well as the increased use of source reduction. We also find that operational leanness has an overall positive effect, i.e., leaner facilities outperform less lean facilities with regard to emissions reductions. However, we find partial support for a negative moderation effect of operational leanness on emissions reductions, i.e., when the relative assessed hazard level increases, less lean facilities increase their emissions reductions more than leaner facilities. In addition, we find partial support for a positive moderation effect of operational leanness on the use of EOP treatment. To the best of our knowledge, our study is the first in the environmental management and sustainable operations literatures to analyze the effects of publicly-disseminated information pertaining to the relative assessed hazard levels of chemicals on the voluntary emissions reduction efforts of facilities using those chemicals, while also providing insights into the implications of operational leanness.

2.2 Literature and Hypotheses

Reinhardt (1999) examined the forces that motivate firms to develop beyond-compliance strategies and to take voluntary environmental actions, and categorized them into one risk-oriented force (i.e., business risk management) and three profit-oriented forces: (i) strategic interaction, (ii) product differentiation, and (iii) free lunch. That is, (i) managers may expect advantages over rivals under imperfect market competition and may strategically take preemptive actions such as interacting with governmental agencies or industrial groups on regulating environmental behaviors, (ii) managers may seek to differentiate their products and command price premiums by incorporating or accounting for environmental externalities, and (iii) managers may enjoy cost savings by exposing existing inefficiencies through beyond-compliance actions. Since the risk-oriented force is the only active force when the immediate economic value of actions beyond compliance is negative, Reinhardt (1999) suggested that this force is the fundamental driver of voluntary actions and claimed that voluntary actions can reduce the probability or magnitude of losses from liability, damage to reputation, and operational disruptions caused by future litigation or changes in regulations. Berry & Rondinelli (1998) also proposed that the increasing cost of merely complying with legal requirements (that gradually become more stringent and complicated) drives firms to take proactive environmental actions. Similarly, Reid & Toffel (2009) proposed that beyond-compliance actions are a preemptive response by firms to mitigate future risks such as additional regulations and more stringent enforcements. Furthermore, when enhancing their risk management systems, firms quantitatively link factors such as customer liability and employee safety to proactive, risk-reducing actions such as pollution prevention (Kleindorfer & Saad 2005).

The dissemination of information about the potential hazards of chemicals and the mandatory disclosure of chemical emissions by facilities result in public awareness of chemical hazards and the environmental implications of facilities operations. This awareness can be expected to lead to pressure on facilities to internalize the risks revealed by the information (Kraft *et al.* 2013). The effects of mandatory disclosure on the use or emissions of chemicals has been examined in different contexts (e.g., Doshi *et al.* 2013, Kalkanci & Plambeck 2015). The literature, however, contains fewer studies pertaining to the effects of information dissemination of chemical hazards by governmental agencies or non-governmental organizations. One of these studies is by Gormley & Matsa (2011), who hypothesized that chemicals newly added to the RoC expose firms that routinely use these chemicals to significantly greater occupational liability in the form of legal fees, damage payments, and insurance premiums. Using an event-study approach, they found that firms exposed to the newly-added chemicals were more likely to take strategic actions such as product diversification or expansion through acquisition, as compared to unexposed firms. Similar to Gormley & Matsa (2011), we contend that facilities associate a higher relative assessed hazard level for a chemical with greater likelihood of new or more stringent regulations, stricter enforcement, higher expected costs of ensuring occupational safety, or greater liability for harm caused by the chemical to employees and the public, and therefore seek to address these risks in the form of voluntary reductions in the emissions of the chemical.

A facility may either limit, at source, the amount of a chemical used within its processes, or treat chemical waste using EOP methods, or perform both. Several studies have indicated the need for facilities to dedicate efforts to both categories of practices in order to achieve reductions in emissions that go beyond compliance (Klassen & Whybark 1999, Rothenberg *et al.* 2001, Kroes *et al.* 2012). Furthermore, Dutt & King (2014) examined the relationship between source reduction and EOP treatment and found evidence that the relationship is not substitutive but complementary. Thus, we posit that in order to respond to an increase in the relative assessed hazard level of a chemical, facility managers may increase the use of source reduction, increase the use of EOP treatment, or both, to achieve reductions in emissions. We therefore hypothesize the following:

H1a: An increase in the relative assessed hazard level of a chemical is positively associated with reductions in emissions of the chemical.

H1b: An increase in the relative assessed hazard level of a chemical is positively associated with the use of source reduction for the chemical.

H1c: An increase in the relative assessed hazard level of a chemical is positively associated with the use of EOP treatment for the chemical.

Closely related to voluntary emissions reductions is the practice of lean operations. Lean operations involves the elimination of non-value-adding activities and waste, the reduction of variability in supply, demand, and internal operations, and the continuous improvement of these actions (Womack *et al.* 1990, Womack & Jones 1996, Hopp & Spearman 2004, Narasimhan *et al.* 2006, Shah & Ward 2007). Studies in the sustainable operations literature suggest that the outcomes of practicing lean—(1) the identification and minimization of waste, including emissions, (2) the empowerment of employees and facilitation of their in-depth know-how of production processes, and (3) continuous improvements in all aspects—help facilities achieve better operational and environmental performance simultaneously, yielding the lean is green concept (King & Lenox 2001, Kleindorfer *et al.* 2005, Corbett & Klassen 2006).

The empirical study by King & Lenox (2001) showed a negative association between the leanness of a facility (measured by the summation of the maximum inventory levels across all chemicals) and its overall emissions, i.e., evidence that leaner facilities have lower overall emissions. Since the benefits of practicing lean, including a focused awareness of waste and enhanced know-how of processes, could facilitate the prioritization of waste reduction efforts and enhance the effectiveness of these efforts, operational leanness can be expected to *positively moderate* emissions reductions when the relative assessed hazard level of a chemical increases.

On the other hand, the literature also identifies certain limitations of leanness in a dynamic environment. When the business environment is dynamic, facilities or firms with closely integrated operations and smoothed production processes resulting from practicing lean are inhibited from adapting (Yusuf & Adeleye 2002, Narasimhan *et al.* 2006). Azadegan *et al.* (2013) found evidence that when a firm operates under sales uncertainty, a negative implication of lean operations on financial performance is likely to surface. Capturing business dynamism in the form of changing intensity of market competition, Eroglu & Hofer (2014) also observed a similar negative effect. In addition, Rothenberg *et al.* (2001) found partial support for a negative association between emissions levels and leanness when environmental managers in automotive assembly plants faced increasingly stringent emissions standards over time. For our context, this would suggest that, when encountering increases in the relative assessed hazard levels of chemicals used in their operations, leaner facilities may not be able to reduce emissions as much as less lean facilities or, that operational leanness may *negatively moderate* the relationship between increases in relative assessed hazard levels and reductions in emissions. Based on the preceding discussion, we offer the following competing hypotheses for the moderating effect of operation leanness:

H2a(b): Operational leanness positively (negatively) moderates reductions in emissions of a chemical when the relative assessed hazard level of the chemical increases.

According to the principles of lean operations, waste and inefficiencies are resolved at the source. Thus, leaner facilities can be expected to use source reduction to a greater extent than less lean ones. Similarly, since EOP methods only symptomatically treat problematic chemicals at the end of the process, leaner facilities would be less likely to employ EOP treatment. Overall, since reducing emissions at the source rather than treating them at the end-of-pipe has a similar logic to incorporating quality at the source rather than inspecting quality at the end of the process, managers at leaner firms can be expected to engage more in source reduction and less in EOP treatment (King & Lenox 2001). Rothenberg *et al.* (2001) found that managers of leaner facilities regard EOP treatment as the last resort, and would rather explore efficiency improvements in production processes than increase the use of EOP treatment unless regulations forced them to do so. Thus, when the relative assessed hazard level of a chemical increases, managers at leaner facilities can be expected to pursue source reduction for the chemical to a greater extent than less lean facilities. Moreover, leaner facilities can be expected to pursue EOP treatment to a lesser extent than less lean facilities. On the other hand, although King & Lenox (2001) proposed that leaner firms would engage less in EOP treatment, they did not find empirical support for this contention. Relatedly, certain empirical studies on lean operations (Azadegan *et al.* 2013, Eroglu & Hofer 2014) have evidenced a trade-off between the minimization of slack and the capability to cope with a dynamic environment; closely integrated production processes at lean facilities may be unamenable to further source reduction activities, resulting in EOP treatment being favored. Thus, when the relative assessed hazard level of a chemical increases, managers at leaner facilities may be less able to implement source reduction and may engage more in EOP treatment compared to managers at less lean facilities. Therefore, we propose the following competing hypotheses:

H3a(b): Operational leanness positively (negatively) moderates the use of source reduction for a chemical when the relative assessed hazard level of the chemical increases.

H4a(b): Operational leanness positively (negatively) moderates the use of EOP treatment for a chemical when the relative assessed hazard level of the chemical increases.

2.3 Data, Variables, and Empirical Approach

2.3.1 Data

As discussed earlier, we use the SPL from the ATSDR (published to the Federal Register biennially) as the data source for the relative assessed hazard levels of chemicals. To determine facility-level voluntary reductions in chemical emissions and the use of source reduction and EOP treatment, we use TRI data from the US EPA. For various facility and industry controls, we draw data from two more sources: the National Establishment Time-Series (NETS) data from Walls & Associates and the Compustat North America annual data from Standard & Poors. The ATSDR did not publish the 2009 SPL because of a transition to a new database. In addition, the EPA expanded the list of chemical substances that firms were required to report to the TRI and lowered the reporting quantity thresholds of persistent bio-accumulative toxic chemicals in 2000. To avoid potential implications of such regulatory changes, we focus on the period 2001-2009. Since the SPL is published biennially, we define event year t based on the schedule of the SPL, i.e., $t \in [2003, 2005, 2007]$, and measure our variables based on these event years. Note that our data spans two years before the earliest event year to two years after the latest event year (i.e., the period 2001-2009) due to our measures of rank changes from the previous event year to the next and emissions following the event years.

Substance Priority List (SPL)

As the lead agency for implementing the health-related provisions of the Comprehensive Environmental Response, Compensation, and Liability Act, ATSDR is charged to assess the presence and nature of health hazards at specific Superfund sites, to help prevent or reduce further exposure and the illnesses that result from such exposures, and to expand the knowledge base about health effects from exposure to hazardous substances (ATSDR 2009).

To determine the relative hazard levels (or the ranks) of chemical substances, the ATSDR aggregates the points assigned to over 800 candidate chemicals based on three criteria: toxicity, frequency of occurrence at polluted sites, and probability of human exposure based on concentration levels and types of exposure to populations around the sites (ATSDR 2014). The chemicals are ranked in descending order based on their total points (i.e., the most hazardous chemical is ranked #1). The top 275 chemicals constitute the SPL and receive substantial focus. For these top 275 chemicals, the ATSDR is responsible for performing additional toxicological tests, preparing detailed toxicological profiles, and distributing the information to state officials, medical administrators, and other health professionals. This information includes educational materials on the surveillance and screening of emissions, and diagnoses and treatments of injuries and diseases related to human exposure to these chemicals (ATSDR 2009, 2012, 2014). We focus our analysis on those chemical substances that appeared in all the SPLs throughout the period of our study, noting that changes in their ranks over time reflect changes in their relative assessed hazard levels[1].

Toxics Release Inventory (TRI)

To capture chemical emissions by facilities and their use of source reduction or EOP treatment, we use data from the TRI Basic Plus (version 12) dataset from the EPA. In addition to the amounts of chemicals released into the environment (air, water, or land) by facilities, the TRI also captures the amounts of the chemicals that are managed through recycling, energy recovery, and treatment (EPA 2016). Chemicals in the TRI data are indexed by Chemical Abstracts Service Registry Numbers, whereas facilities are indexed by facility identification (FID) numbers assigned by the EPA. We illustrate the data captured in the TRI using the conceptual waste flows in Figure 2.1. After merging the TRI data with the SPL, we obtain a panel dataset with 43,400 observations, spanning 120 chemical substances and 9,130 facilities over the period 2001-2009.

[1] Only a total of 10 TRI-listed chemicals moved either in or out of the top 275 over the period of our study

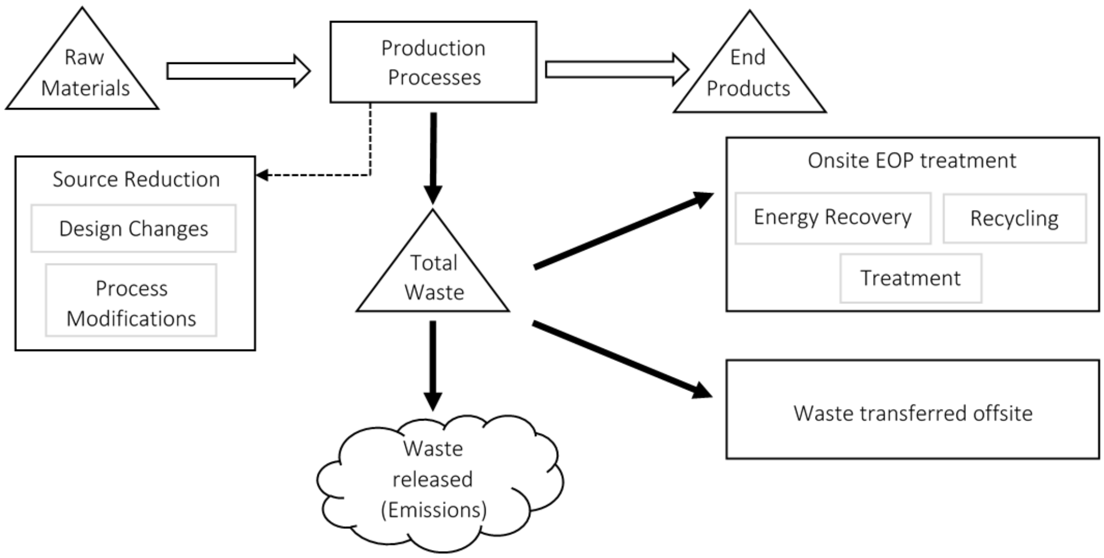

Figure 2.1: Waste flows captured in TRI data

Notes: Black arrows denote waste flows. The dotted line represents the effect of source reduction on the waste generated from production processes. For each chemical c at facility i during year t, the TRI data includes the amount of waste released ($Release^{i,c,t}$), the amounts of waste processed under energy recovery ($EnergyRecovered_{i,c,t}$), recycling ($Recycled_{i,c,t}$), and treatment ($Treated_{i,c,t}$), and the amount of waste transferred offsite ($TransferredOffsite_{i,c,t}$).
Thus,

$$\begin{aligned} TotalWaste_{i,c,t} = Release_{i,c,t} \\ +EnergyRecovered_{i,c,t} + Recycled_{i,c,t} + Treated_{i,c,t} \\ +TransferredOffsite_{i,c,t} \end{aligned}$$

And,

$$EOP_{i,c,t} = EnergyRecovered_{i,c,t} + Recycled_{i,c,t} + Treated_{i,c,t}$$

Compustat and NETS

For additional facility and industry information, we supplemented the merged SPL and TRI data with National Establishment Time Series (NETS) and Compustat data. We first matched the Dun and Bradstreet (DUNS) numbers in the NETS data with the EPA FIDs to pull facility information such as SIC code and number of employees. Since facilities may relocate and report to the TRI under various FIDs while their DUNS numbers remain the same, we used the DUNS number as the primary facility identifier in assembling our dataset. For our industry-level measures, we use data from Compustat and Compustat Segments (which reports data by industry for firms that operate across multiple industries).

2.3.2 Variables and Measures

We employ a panel model that controls for various facility and industry factors. Below, we discuss the dependent variables, main independent variables, and controls included in our model.

Dependent Variables

Emissions Reductions: Since the SPL is biennial, we define event year t based on the release year of the SPL, i.e., $t \in [2003, 2005, 2007]$. Because the SPL for an event year typically becomes publicly available at the end of the year or the beginning of the following year[2], to avoid contamination, we consider the difference in emissions between the event year and the second year after the event year. Specifically, we measure facility is emissions reductions of chemical c as the ratio of the total quantity of the chemical released during the second year after the event year, i.e., $Release_{i,c,t+2}$ to the quantity released during the event year, i.e., $Release_{i,c,t}$. To suppress the effect of extreme values but maintain approximate linearity of the ratio around the mode, we take the natural logarithm of the

[2]The 2003 SPL was published in November 2003, the 2005 SPL was published in December 2005, and the 2007 SPL was published in March 2008.

ratio and multiply it by 100. As a result, for moderate values of the ratio, our measure can be regarded as an approximate percentage change (Kesavan *et al.* 2010, Dutt & King 2014). Lastly, for ease of interpretation, we apply a negative sign to the ratio to arrive at the emissions reductions ($ER_{i,c,t}$) for chemical c at facility i for event year t, as:

$$ER_{i,c,t} = -100 \times \ln\left(\frac{Release_{i,c,t+2}}{Release_{i,c,t}}\right)$$

Use of source reduction: Source reduction (or pollution prevention), includes changing product designs and modifying production processes to *avoid* pollution or waste. We capture a facilitys use of source reduction for a chemical as the change in the total amount of waste of the chemical generated by the facilitys production processes (see Figure 2.1). Using the TRI data, we calculate the total waste ($TotalWaste_{i,c,t}$) for chemical c at facility i in year t by summing the quantities released, treated onsite, and transferred offsite, and measure the use of source reduction ($SR_{i,c,t}$) as:

$$SR_{i,c,t} = -100 \times \ln\left(\frac{TotalWaste_{i,c,t+2}}{TotalWaste_{i,c,t}}\right)$$

Use of EOP treatment: EOP treatment (or pollution control) includes the use of equipment or methods to burn, recycle, or neutralize (i.e., *treat*) pollutants. We capture the change in the use of EOP treatment for a chemical at a facility as the ratio of the quantity of waste of the chemical treated at the end of pipe onsite during the second year after the event year to the quantity treated during the event year. In other words, we measure facility is change in the use of EOP treatment($\Delta EOP_{i,c,t}$) for chemical c and event year t, as:

$$\Delta EOP_{i,c,t} = 100 \times \ln\left(\frac{EOP_{i,c,t+2}}{EOP_{i,c,t}}\right)$$

Independent Variables

Change in relative assessed hazard level of a chemical: To capture the change in the relative assessed hazard level of a chemical, we use a categorical measure, $RelHazard_{c,t}$, which indicates the direction of change in the rank ($Rank_{c,t}$) of chemical c in event year t. Thus,

$$RelHazard_{c,t} = \begin{cases} \text{Increased if} & Rank_{c,t} < Rank_{c,t-2} \\ \text{Decreased if} & Rank_{c,t} < Rank_{c,t-2}. \\ \text{No Change if} & Rank_{c,t} = Rank_{c,t-2} \end{cases}$$

We observed from the SPL data that the *No Change* group typically included chemicals at the top of the list (average rank of 49) whereas the *Increased* and *Decreased* groups were more similar in the spread of the ranks of chemicals within them (average ranks of 140 and 177, respectively). We therefore choose the Decreased group as the reference group for our analysis.[3]

Operational leanness. Lean operations closely relates to practices that minimize buffer stocks or inventories. We construct a facility-level measure of leanness similar to the use-of-inventory measure developed by King & Lenox (2001). For this purpose, we utilize data on the maximum inventories of chemicals reported by each facility to the TRI. The maximum inventory of a chemical at a facility is the maximum total quantity of the chemical across storage tanks, process vessels, on-site shipping containers, etc. at the facility at any time during the reporting year.[4] Using TRI data, we calculate the average of the maximum inventories of the chemicals at a facility in the year subsequent to the event year[5], take the natural logarithm of this average, and mean-center the resulting value by industry at

[3]We performed a Chow test (Chow 1960, Greene 2003) to examine whether there are significant differences in parameter distributions between the *No Change* group and the *Increased* and *Decreased* groups. The test failed to reject the null hypothesis of insignificant differences and we therefore include all three groups in our estimations.

[4]Other aspects of practicing lean beyond inventory use, while of potential interest, are precluded from consideration because of the limited availability of data.

[5]For each event year t, we measure operational leanness and the controls for market concentration and facility size in year $t + 1$. However, our main results remain largely unchanged if for each event year t, we measure them either in year $t + 2$ or as averages across years $t + 1$ and $t + 2$.

the three-digit SIC level to account for differences across industries (Hendricks & Singhal 2009, Eroglu & Hofer 2014). Since a lower value of this measure, $MaxInv_{i,t}$, for facility i and event year t indicates more efficient utilization of buffer stocks compared to industrial peers, or leaner operations (King & Lenox 2001), for ease of interpretation, we set our measure of leanness to be the negative of $MaxInv_{i,t}$; i.e., $Leanness_{i,t} = -MaxInv_{i,t}$.

Control Variables

We employ a variety of controls to account for factors that may explain emissions reduction efforts in response to changes in the relative assessed hazard levels of chemicals.

Market concentration: The studies by Arora & Cason (1995) and Fernndez-Kranz & Santal (2010) found the intensity of industry competition to be associated with voluntary environmental actions. To control for this potential effect, we compute the Hirschman-Herfindahl Index (HHI) at the three-digit SIC level using Compustat data, for the year subsequent to the event year. A higher HHI indicates a higher market concentration or lower intensity of competition.

Industry growth: To control for industry growth or decline, we employ a measure that captures changes in total industry sales using data from Compustat. Although Compustat data does not include information for private firms, we use the total sales of all public firms in an industry as a proxy for total industry sales. Specifically, we calculate the ratio of total sales of all public firms in an industry (at the three-digit SIC level) during the second year after the event year to the total sales during the event year, take the natural logarithm of this ratio, and multiply it by 100.

Operating scale change: The operating scale of a facility may affect its production, waste generation, and thus, emissions. Using data from NETS, we measure changes in scale as the ratio of facility sales during the second year after the event year to the sales during the event year; we take the natural logarithm of this ratio and multiply it by 100.

Facility size: To control for the effect of facility size on voluntary emissions reduction efforts (e.g., Arora & Cason 1995, King & Lenox 2002), we use the natural logarithm of the number of employees at the facility in the year subsequent to the event year. Since the effect of facility size can be non-linear (Arora & Cason 1995), we also incorporate its squared term.[6]

Operational complexity: The overall scope and complexity of a facilitys operations and environmental management efforts may have implications for the emissions reductions efforts for individual chemicals. To account for this potential effect, we incorporate the number of chemicals reported to the TRI by the facility in the event year as a control.

Lagged dependent variables: We incorporate lagged dependent variables to control for diminishing returns to environmental efforts (Beavis & Dobbs 1986, Hartl 1992). In other words, we expect that the emissions reductions achievable during a period would be negatively associated with the emissions reductions during the prior period. Since the effect can be expected to be nonlinear, we also incorporate squared terms of the lagged dependent variables.

Table 2.1 reports descriptive statistics and correlations.

2.3.3 Empirical Approach

Although we control for a variety of facility and industry-level factors that may influence the extent of emissions reductions and the use of source reduction or EOP treatment, to address unobserved heterogeneous characteristics among facilities and chemicals, we employ a (panel) model that includes facility-chemical fixed effects. We also incorporate time fixed effects to account for temporal conditions. A Hausman test supported this fixed effects specification over a random effects specification ($\chi^2 = 3054.07$ with $p = 0.000$). In addition, to address heteroskedasticity, we employ robust standard errors throughout our analyses. To test for the moderating effect of operational leanness, we incorporate an interaction term between change in relative assessed hazard level and operational leanness.

[6] Our main results remain unchanged if we use facility sales as a measure of size instead of number of employees.

Table 2.1: Descriptive statistics and correlations

	Variables	Mean	S.D.	1	2	3	4	5	6	7	8	9	10	11
1	Emissions reductions	15.103	129.813											
2	Source reduction	11.995	125.698	0.440**										
3	Change in the use of EOP treatment	-9.016	126.165	-0.227**	-0.760**									
4	RelHazard = Increase	0.336	0.472	0.020**	0.015**	-0.020**								
5	RelHazard = Decrease	0.323	0.467	-0.025**	-0.031**	0.042**	-0.491**							
6	RelHazard = No Change	0.341	0.474	0.005	0.016**	-0.023**	-0.512**	-0.497**						
7	Leanness	0.000	0.354	0.009	0.013**	-0.024**	-0.052**	-0.034**	0.086**					
8	Market concentration	0.158	0.160	0.015**	0.019**	-0.011	0.005	-0.009	0.003	-0.02				
9	Industry growth	-0.412	68.866	-0.017**	- 0.014**	-0.000	-0.008	0.022**	-0.030**	-0.007	-0.084**			
10	Operating scale change	-1.416	66.685	-0.004	-0.003	0.003	-0.026**	0.023**	0.003	0.001	0.012**	-0.018**		
11	Facility size	4.785	1.563	0.004	-0.010*	0.012	0.041**	0.016**	-0.057**	-0.007	0.104**	-0.018**	-0.221**	
12	Operational complexity	11.925	20.145	-0.048**	-0.020**	0.018**	-0.002	-0.034**	-0.032**	0.006	-0.035**	-0.007	-0.027**	0.074**

Note: ** $p<0.01$, * $p<0.05$

Thus:

Our empirical model for testing H1a and H2a(b) is:

$$\begin{aligned} ER_{i,c,t} = &\beta_1 RelHazard_{c,t} + \beta_2 Leanness_{i,t} + \beta_3 (RelHazard_{c,t} \times Leanness_{i,t}) \\ &+ \lambda \mathbf{Z}_{i,c,t} + \alpha_{i,c} + \mu_t + \varepsilon_{i,c,t} \end{aligned} \tag{2.1}$$

Our empirical model for testing H1b and H3a(b) is:

$$\begin{aligned} SR_{i,c,t} = &\beta_1 RelHazard_{c,t} + \beta_2 Leanness_{i,t} + \beta_3 (RelHazard_{c,t} \times Leanness_{i,t}) \\ &+ \lambda \mathbf{Z}_{i,c,t} + \alpha_{i,c} + \mu_t + \varepsilon_{i,c,t} \end{aligned} \tag{2.2}$$

Our empirical model for testing H1c and H4a(b) is:

$$\begin{aligned} \Delta EOP_{i,c,t} = &\beta_1 RelHazard_{c,t} + \beta_2 Leanness_{i,t} + \beta_3 (RelHazard_{c,t} \times Leanness_{i,t}) \\ &+ \lambda \mathbf{Z}_{i,c,t} + \alpha_{i,c} + \mu_t + \varepsilon_{i,c,t} \end{aligned} \tag{2.3}$$

In the models above, $\alpha_{i,c}$ represents facility-chemical fixed effects, μ_t represents time fixed effects, and $\mathbf{Z}_{i,c,t}$ is the set of control variables.

2.4 Results

We present our main results in Table 2.2. Models 1-1 to 1-3 in Table 2.2 include only the control variables in equations (2.1), (2.2), and (2.3) above, respectively. Notably, the coefficients of the lagged dependent variables are all significant and consistently suggest diminishing returns to emissions reduction efforts. The effect of operational complexity is significant and negative in Model 1-1, indicating a negative relationship between the scope of environmental management efforts and emissions reductions for individual chemicals. In addition, we find a U-shaped relationship between facility size and emissions reductions (including the use of source reduction); specifically, small and large-size facilities are associated with greater emissions reductions as well as greater use of source reduction as compared to mid-size facilities. Also, we find that facilities in industries with higher market concentrations are associated with greater emissions reductions.

Models 2-1 to 2-3 in Table 2.2 incorporate the independent measure $RelHazard_{c,t}$, which indicates the direction of change in the relative assessed hazard level of chemical c

Table 2.2: Main results

Variables	Model 1-1 ER	Model 1-2 SR	Model 1-3 ΔEOP	Model 2-1 ER	Model 2-2 SR	Model 2-3 ΔEOP	Model 3-1 ER	Model 3-2 SR	Model 3-3 ΔEOP
RelHazard = No Change				-1.38 (0.54)	0.28 (0.90)	-4.66 (0.21)	-1.50 (0.51)	-0.05 (0.98)	-4.25 (0.25)
RelHazard = Increase				4.84** (0.02)	3.42* (0.06)	-1.08 (0.73)	4.68** (0.02)	3.39* (0.06)	-0.04 (0.74)
Leanness							11.88** (0.03)	11.97** (0.02)	-22.01** (0.02)
Leanness when RelHazard = No Change							-2.08 (0.77)	-13.18* (0.07)	19.48 (0.19)
Leanness when RelHazard = Increase							-4.62 (0.47)	-0.59 (0.91)	14.43 (0.14)
Market concentration	21.61*** (0.02)	15.44 (0.13)	8.55 (0.57)	20.68** (0.03)	14.77 (0.15)	7.98 (0.59)	21.49** (0.02)	15.96 (0.12)	9.04 (0.55)
Industry growth	-0.00 (0.87)	-0.01 (0.55)	0.05*** (0.00)	-0.00 (0.89)	-0.01 (0.56)	0.05*** (0.00)	-0.00 (0.86)	-0.01 (0.52)	0.05*** (0.00)
Operating scale change	-0.00 (0.80)	0.01 (0.45)	-0.02 (0.40)	-0.00 (0.81)	0.01 (0.45)	-0.02 (0.40)	-0.00 (0.83)	0.01 (0.43)	-0.02 (0.33)
Facility size	-15.81*** (0.00)	-20.69*** (0.00)	11.90 (0.19)	-15.69*** (0.00)	-20.60*** (0.00)	11.92 (0.10)	-15.68*** (0.00)	-20.63*** (0.00)	11.63 (0.20)
Facility size∧2	1.61*** (0.01)	2.46*** (0.00)	-1.32 (0.18)	1.59*** (0.01)	2.45*** (0.00)	-1.33 (0.18)	1.59*** (0.01)	2.45*** (0.00)	-1.32 (0.18)
Operational complexity	-1.54*** (0.00)	0. 06 (0.83)	-0.29 (0.26)	-1.54*** (0.00)	0.06 (0.82)	-0.29 (0.26)	-1.70*** (0.00)	-0.06 (0.83)	-0.18 (0.48)

Table 2.2: Main Results (*Continued*)

Variables	Model 1-1 ER	Model 1-2 SR	Model 1-3 ΔEOP	Model 2-1 ER	Model 2-2 SR	Model 2-3 ΔEOP	Model 3-1 ER	Model 3-2 SR	Model 3-3 ΔEOP
Lagged ER	-0.41***			-0.41***			-0.41***		
	(0.00)			(0.00)			(0.00)		
Lagged ER∧2	-0.00*			-0.00***			-0.00***		
	(0.00)			(0.00)			(0.00)		
Lagged SR		-0.45***			-0.45***			-0.45***	
		(0.00)			(0.00)			(0.00)	
Lagged SR∧2		-0.00**			-0.00**			-0.00**	
		(0.02)			(0.02)			(0.02)	
Lagged ΔEOP			-0.46***			-0.46***			-0.46***
			(0.00)			(0.00)			(0.00)
Lagged ΔEOP∧2			-0.00***			-0.00***			-0.00***
			(0.01)			(0.01)			(0.01)
Observations	43400	43400	14622	43400	43400	14622	43400	43400	14622
R-squared	0.2138	0.2287	0.2345	0.2140	0.2288	0.2347	0.2142	0.2291	0.2353

Notes: Robust p-values in parentheses: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$; The estimated coefficients for *RelHazard* = *No Change* are grayed out for readability; Fixed effect estimates are omitted for brevity.

in event year t. We find that an increase in relative assessed hazard level is significantly associated with greater emissions reductions as well as greater use of source reduction ($\beta_1 = 4.84$ with $p = 0.02$ when *RelHazard* = *Increased* in Model 2-1; and $\beta_1 = 3.42$ with $p = 0.06$ when *RelHazard* = *Increased* in Model 2-2). In other words, when the relative assessed hazard level of a chemical increases, facilities reduce emissions by an additional 4.84% on average compared to when the relative assessed hazard level decreases. Also, the use of source reduction increases by an average of 3.42%. However, we do not find a significant association between an increase in relative assessed hazard level and the use of EOP treatment ($\beta_1 = -1.08$ with $p = 0.73$ in Model 2-3). Thus, H1a and H1b are supported, but not H1c.

Models 3-1 to 3-3 incorporate the interaction between change in relative assessed hazard level and operational leanness. From the results of Model 3-1, we observe that when the relative assessed hazard level *decreases*, the coefficient of Leanness is positive and significant ($\beta_2 = 11.88$ with $p = 0.03$). That is, leaner facilities are associated with significantly greater reductions in emissions than less lean facilities when the relative assessed hazard level decreases. However, when the relative assessed hazard level *increases*, there is an insignificant difference in emissions reductions between leaner and less lean facilities (when *RelHazard* = *Increased*, $\beta_2 + \beta_3 = 7.25$ with a Wald-test $p = 0.193$). This suggests partial support for a *negative* moderation effect of operational leanness on emissions reductions (H2b). Figure 2.2 plots the predicted emissions reductions for leaner and less lean facilities (including the 90% confidence intervals) depending on whether the relative assessed hazard level increases or decreases.

The results of Model 3-2 show that, when the relative assessed hazard level *decreases* or *increases*, the estimated coefficients of operational leanness are positive and significant ($\beta_2 = 11.97$ with $p = 0.02$; and $\beta_2 + \beta_3 = 11.39$ with a Wald-test $p = 0.03$ when *RelHazard* = *Increased*), suggesting that the use of source reduction at leaner facilities is greater than that at less lean facilities when the relative assessed hazard levels either

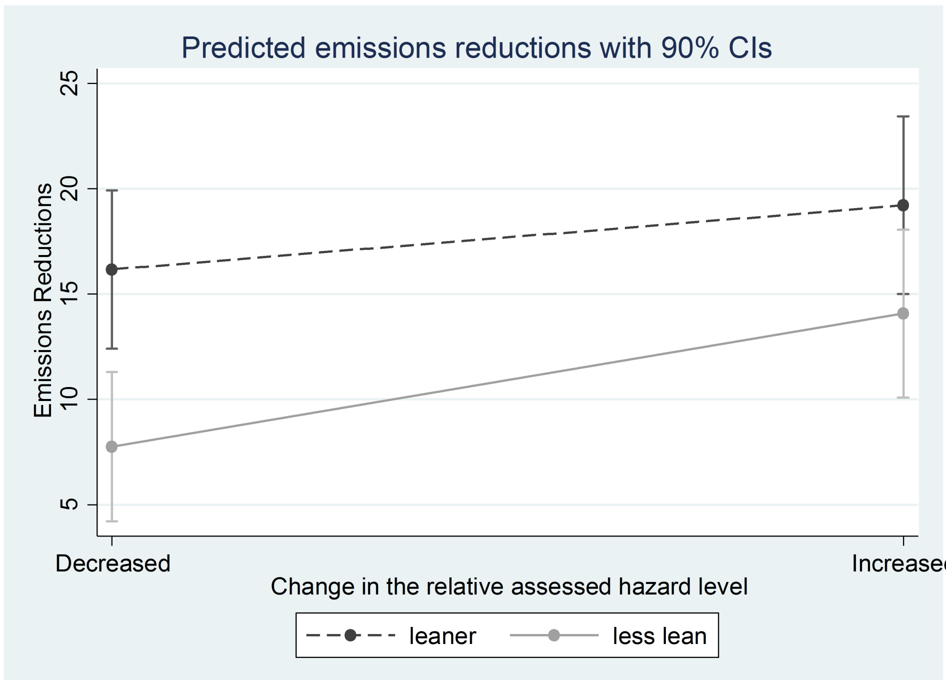

Figure 2.2: Predicted reductions in emissions for leaner and less lean facilities when the relative assessed hazard level increases/decrease

Notes: To illustrate the effect of operational leanness, we set the Leanness value for a leaner facility to be one standard deviation above the mean value of Leanness (i.e., $\mu_{Leanness} + \sigma_{Leanness}$) whereas we set the value for a less lean facility to be one standard deviation below the mean value (i.e., $\mu_{Leanness} - \sigma_{Leanness}$), where $\sigma_{Leanness} = 0.364$. As a result, the distance between the lines in Figure 2.2 for leaner and less lean facilities is $\beta_2 \times 2\sigma_{Leanness}$ when the relative assessed hazard level decreases and $(\beta_2 + \beta_3) \times 2\sigma_{Leanness}$ when the relative assessed hazard level increases.

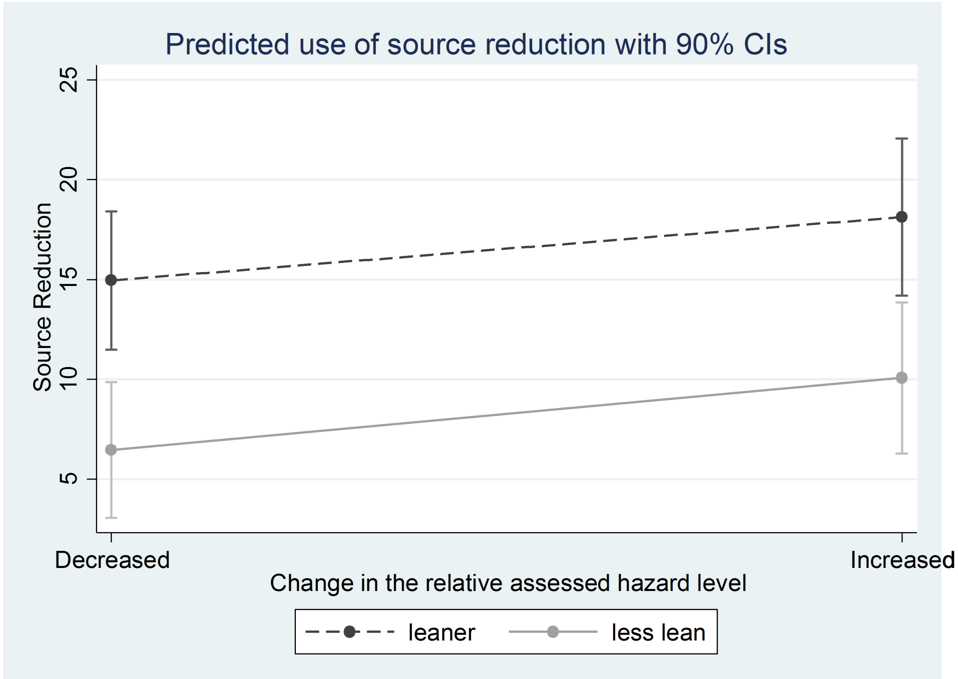

Figure 2.3: Predicted use of source reduction for leaner and less lean facilities when the relative assessed hazard level increases/decrease

increase or decrease, and that operational leanness does not moderate the use of source reduction. Thus, neither H3a nor H3b is supported. Figure 3 plots the predicted use of source reduction. Note that the lines for leaner and less lean facilities in Figure 2.3 are almost parallel to each other and the confidence intervals do not overlap.

The results of Model 3-3 show that, when the relative assessed hazard level *decreases*, the coefficient of Leanness is negative and significant ($\beta_2 = -22.01$ with $p = 0.02$). In other words, when the relative assessed hazard level decreases, the use of EOP treatment at leaner facilities decreases by a greater extent than that at less lean facilities. However, the coefficient is insignificant when the relative assessed hazard level increases ($\beta_2 + \beta_3 = -7.57$ with a Wald-test $p = 0.41$ when *RelHazard* = *Increased*). Thus, our findings suggest partial support for a *positive* moderation effect of operational leanness on the use of EOP treatment (H4a). We illustrate this finding in Figure 2.4. We also note the following *overall effects of operational leanness*. The overall effect of operational leanness on emissions reductions is positive and significant (when *Leanness* is added to Model 1-1, its coefficient

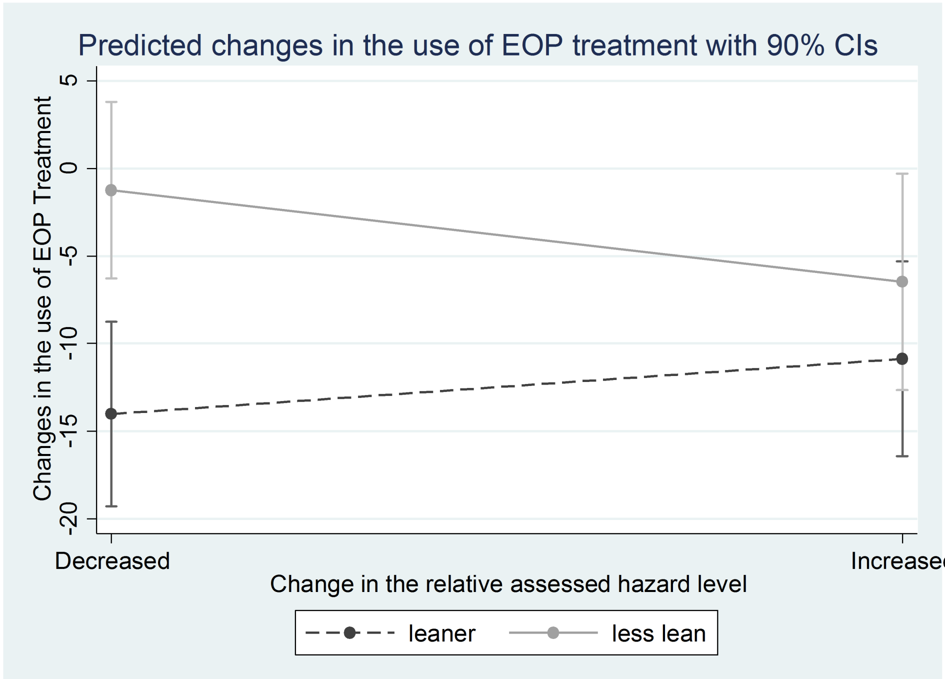

Figure 2.4: Predicted changes in the use of EOP treatment for leaner and less lean facilities when the relative assessed hazard level increases/decrease

is 9.70 with $p = 0.023$). Overall, operational leanness is also weakly positively associated with source reduction (when *Leanness* is added to Model 1-2, its coefficient is 7.39 with $p = 0.097$) and insignificantly associated with the use of EOP treatment (when *Leanness* is added to Model 1-3, its coefficient is -10.94 with $p = 0.117$).

2.5 Robustness Checks

We examine the robustness of our main findings (i.e., support for H1a and H1b, and partial support for H2b and H4a) to: (i) alternative measures of our main independent variable (change in relative assessed hazard level), (ii) expansion of the set of chemicals considered in our sample (from a focus on the top 275 to all chemicals in the SPL), and (iii) consideration of additional explanatory factors. Tables of results for the robustness checks are included in the Appendix.

(i) *Alternative measures of main independent variable (change in relative assessed hazard level):*

(a) As mentioned earlier, to determine the relative hazard levels of chemicals (or their ranks), the ATSDR aggregates and publicly reports the points assigned to chemicals based on three criteria: toxicity, frequency of occurrence at polluted sites, and probability of human exposure based on concentration levels and types of exposure to populations around polluted sites (ATSDR 2014). As an alternative to using the direction of change in rank, we calculated the *ratio of the total points received by a chemical in the event year, to the total points received in the prior event year*. Since the total points assessed for chemicals generally increase over time as the ATSDR researches additional polluted sites, we mean-centered this ratio across all chemicals, by event year. A positive mean-centered ratio for a chemical indicates an above-average increase in its assessed hazard level ($PointsRatio_{c,t} > 0$). On the other hand, a negative mean-centered ratio for a chemical indicates a below-average increase in its assessed hazard level ($PointsRatio_{c,t} < 0$). The results of the corresponding models with this alternative independent measure (reported in Appendix Table A.1.) similarly support H1a, H1b, H2b, and H4a, as before. Additionally, we find partial support for H3b, i.e., operational leanness *negatively* moderates the use of source reduction for a chemical when the relative assessed hazard level of the chemical–measured as *PointsRatio*– increases.

(b) Recall that we used a categorical measure, $RelHazard_{c,t}$, in our main analysis to capture the *direction of change* in the rank of a chemical in an event year. However, the numerical rank of the chemical could itself play a role in the emphasis placed on the chemical for emissions reductions efforts (analogous to the order effects observed by Muthulingam *et al.* 2013 in the adoption of energy efficiency recommendations). In order to capture the magnitude of change in the hazard assessment of a chemical relative to its position on the SPL, we calculated the *ratio of a chemicals rank in the event year, to its rank in the prior event year*. We then took the natural logarithm of this ratio, applied a negative sign, and interacted the resulting ratio ($RankRatio_{c,t}$) with $RelHazard_{c,t}$ to dichotomize it according to the direction of rank change. The results of the corresponding models with these independent measures (reported in Appendix Table A.2) similarly support H1a, H2b, and H4a, as before. However, we do not find support for H1b ($p = 0.11$), i.e., we do not find sufficient evidence to support the hypothesis that an increase in the relative assessed hazard level of a chemical is positively associated with the use of source reduction for the chemical.

(ii) *Expansion of set of chemicals considered in the sample:*

We expanded our sample to include all chemicals that appeared in the SPLs over the period of our study, beyond the top 275 that receive significant subsequent attention. The expanded sample contains 65,533 observations (10,623 facilities and 215 chemicals). Since chemicals ranked low in the SPL experience excessive rank changes arising from only minor changes in total assessed points, we employed the alternative independent measure $PointsRatio_{c,t}$ as in the robustness check *i(a)* above. Results (reported in Appendix Table A3) similarly support H1a, H1b, H2b, and H4a, as before. Additionally, H3b is also partially supported.

(iii) *Additional explanatory factors:*

(a) Chemicals that exhibit more dramatic changes in ranks on the SPL (i.e., greater rank variance across event years), may induce voluntary environmental actions to a different extent than chemicals whose ranks are more stable. Using a rolling nine-year rank history, we calculated the rank variance-to-mean ratios ($RankVartoMeanRatio_{c,t}$) for the chemicals for each event year (2003, 2005, and 2007). We additionally interacted this variance measure with $RelHazard_{c,t}$, to account for the potential difference in the effects of rank uncertainty when the relative assessed hazard level increases versus when it decreases. The results (reported in Appendix Table A4) similarly support H1a, H1b, H2b, and H4a, as before. Furthermore, we find evidence for the increased use of EOP treatment when the relative assessed hazard level increases for chemicals with greater rank uncertainty.

(b) Earlier studies have suggested that local environmental preferences may influence the voluntary environmental actions of managers. As a measure of environmental preferences local to the state in which a facility is located, we used data from the National Environmental Scorecard published by the League of Conservation Voters. Similar to Doshi *et al.* (2013), we used the percentage of environmental bills that were favored by members of the US House of Representatives, by state, in the year following the event year. We mean-centered this score (*LCVH*) by year and interacted it with $RelHazard_{c,t}$. The results (reported in Appendix Table A5) similarly support H1a, H1b, H2b, and H4a, as before. While this measure of local environmental preferences is not significantly associated with emissions reductions (similar to the results in Doshi et al. 2013), we do find evidence of a significant and positive relationship with respect to the use of source reduction (coefficient of *LCVH* in Model 2 is 0.30 with $p = 0.01$).

(c) Voluntary environmental actions may depend on the degree of regulatory attention or scrutiny received by an industry. To contrast the pollution damages of industries with their net contributions to national output, Muller *et al.* (2011) estimated the marginal damages of major air pollutants and factored the emitted quantities in 2006 to derive the gross environmental damages (GEDs) of industries at the six-digit NAICS level. They then calculated the ratio of the GED of an industry to the value added (VA) by the industry. The VA of an industry is calculated as the market value of outputs less that of inputs, not including labor, land, and capital (using data from the US Bureau of Economic Analysis and the US Census Bureaus Economic Census). We recomputed the year-2006 GED/VA values at the three-digit NAICS level and mean-centered these values. Thus, if the ratio for an industry is positive, the industry is likely under-regulated, and if the ratio is negative, the industry is likely over-regulated. We incorporated this additional measure, *GED_VA_Ratio*, in our model and interacted it with *RelHazard*. The results (reported in Appendix Table A6) show that facilities in over-regulated industries are associated with greater reductions in emissions as well as greater use of source reduction when the relative assessed hazard level increases (the coefficient of *GED_VA_Ratio* when *RelHazard* = *Increased* is -0.48 with $p = 0.02$ in Model 4, and is -0.30 with $p = 0.09$ in Model 5). Furthermore, the results continue to show similar support for H1a, H1b, H2b, and H4a.

2.6 Discussion

With the increasing use of chemicals and growing concerns regarding their potential hazards to human health and the environment, understanding how firms respond to the dissemination of public information on the relative hazards of chemicals is important for researchers, policymakers, environmental managers, and society as a whole. We describe the contributions of our research below.

To the best of our knowledge, ours is the first study in the environmental management and sustainable operations literatures to empirically examine firms voluntary environmental actions in response to the dissemination of public information about the relative hazards of chemicals. We find evidence that this public information dissemination is effective, as indicated by the significant association between increases in the relative assessed hazard levels of chemicals and greater subsequent emissions reductions. Our findings therefore suggest that facilities may recognize changes in the relative assessed hazard levels of chemicals and internalize the associated risks by undertaking voluntary actions accordingly. In addition, we find that in dealing with chemicals with increasing relative hazard, managers devote greater effort to source reduction, which has also been suggested in the prior literature to be a strategically better option than EOP treatment (Hart & Ahuja 1996, Klassen & Whybark 1999, King & Lenox 2002, Kroes *et al.* 2012).

With regard to the implications of operational leanness, we find that its overall effect is positive, i.e., leaner facilities outperform less lean facilities with regard to emissions reductions. However, we find that leaner and less lean firms may respond differently in dealing with chemicals with increasing relative hazard. In particular, when relative assessed hazard levels increase, managers in less lean facilities increase their emissions reductions more than managers in leaner facilities. We propose two potential explanations for this observation: first, the adoption of lean practices provides internal incentives for eliminating waste and reducing emissions (Treville & Antonakis 2006). In the absence of such internal incentives, information about the relative hazards of chemicals can help managers in less lean facilities prioritize their environmental actions. Second, smoothed production processes and minimized operational slacks may restrain managers in leaner facilities from achieving further emissions reductions (and, in particular, source reductions) in response to increases in relative assessed hazard. Consistent with this second explanation and in contrast with the dominant view in the sustainable operations literature that lean facilities limit the use of EOP treatment (Rothenberg *et al.* 2001, King & Lenox 2002), we find partial support for a positive moderation effect of operational leanness on the use of EOP treatment when the relative assessed hazard level increases.

For policymakers and planners designing information-based regulations and environmental programs, our findings support the notion of disseminating public information to influence firms prioritization of voluntary environmental actions. We believe that our results can be used by organizations such as ATSDR to predict the effects of informational updates on firms reductions of chemical emissions. In addition, we show that the effectiveness of an information dissemination program is subject to operational and demographical characteristics of targeted facilities (with evidence, for example, that facilities that are less lean or that are in relatively over-regulated industries are more responsive to increases in relative assessed hazard). Understanding the implications of these characteristics and anticipating differences in responses will be particularly helpful for policymakers and planners in designing or refining such programs.

For environmental managers, we suggest that the assertion of lean is green is robust even after accounting for changing assessments of chemical hazards. However, we provide new insights into the consequences of practicing lean. Managers contemplating the application of lean practices should be cautioned against overestimating the extent of emission reductions achievable in response to increases in relative assessed hazard levels of chemicals. In addition, and in contrast to the majority view in the environmental management and sustainable operations literatures that the use of EOP treatment should be avoided in favor of source reduction, we observe that managers in leaner facilities with limited operational slack may need to leverage EOP treatment to respond to increases in relative assessed hazard. A more thorough understanding of these consequences is critical for assessing the continuing environmental objectives achievable by the implementation of lean practices.

We recognize that our findings may be subject to the data sources that we use for our independent and dependent measures. First, we leverage the ranks of chemicals in the SPL as a measure of their relative assessed hazard levels. Although hazard assessments are closely tied to the methodologies employed, we believe that the exhaustive nature of the quantitative assessments by ATSDR, its federal charter to conduct public health assessments, and its authority to assist the US EPA in determining which substances should be regulated and the levels at which substances may pose a threat to human health, render the SPL ranks of chemicals as perhaps the most credible source available for the relative hazards of chemicals. Second, although reductions in emissions reported to the TRI have been widely recognized and employed as a measure of voluntary environmental actions by facilities (Hart 1995, King & Lenox 2001, Doshi *et al.* 2013), it is self-reported as opposed to data from continuous emissions monitoring systems for example. However, monitoring systems for the 650-plus chemicals reported under the TRI program would be very challenging and appear unlikely. Instead, we expect penalties for TRI non-compliance to continue into the foreseeable future. Finally, while lean practices include additional principles such as the development of employee skills and the implementation of quality management systems, our study leverages the use of inventory buffers as a measure of leanness. Although challenging to capture for both public and private facilities from secondary data, it would be interesting to examine the implications of other measures of leanness on the response to changing hazard assessments.

Notwithstanding the above, our findings are quite robust to: (i) alternative measures of our main independent variable (change in relative assessed hazard level), (ii) expansion of the set of chemicals considered in our sample (from a focus on the top 275 to all chemicals in the SPL), and (iii) consideration of additional explanatory factors. Moreover, our study is an initial step towards understanding the effects of information dissemination in the context of managing chemical emissions. The dissemination of information on chemical hazards may have different implications on the use of chemicals in production processes versus their use within products; it will be worthwhile to contrast the effects on voluntary environmental actions in these two scenarios. In addition, other factors such as the characteristics of an information dissemination program (e.g., frequency with which information is updated), the attributes of institutions (e.g., locations of facilities and community demographics), and managers incentives and attitudes towards risk could magnify or dampen the effects of information dissemination. The exploration of such factors is an avenue for future research.

CHAPTER 3
PRODUCT WARRANTY LENGTHS AND SECONDARY MARKET INTERFERENCE

3.1 Introduction

Product warranties are contracts that specify producers' obligation to customers in the event of a product not meeting its original design specifications over a defined time frame. In addition, product warranties are prevalent and regarded as an essential product attribute (Menezes & Currim 1992, Chu & Chintagunta 2008). The literature offers four economic rationales for warranties that benefit a producer: protecting customers against undesirable product defects (insurance), signaling product reliability unobservable to customers (signaling), segmenting customers by their risk preference (sorting), and incentivizing the producer to improve its products (incentive). For further detail on these rationales, please refer to Emons (1989).

Past studies have also investigated producers' decisions regarding their warranty lengths, the most prominent feature in product warranties (Menezes & Currim 1992, Chu & Chintagunta 2008, 2011), and have suggested that a longer warranty can compensate for customers' concerns regarding product reliability (Heal 1977, Chu & Chintagunta 2011, Thomas 2006). A recent study by Guajardo *et al.* (2016) estimates that an additional year of a warranty in the US automobile market has value-added equivalent to 3.1% of the median vehicle price, and finds that the value-adding effect increases when the reliability of a model is perceived to be lower. However, our understanding regarding producers' warranty-length decisions is still limited. For example, while earlier studies provide mixed evidence regarding the relationship between product reliability and warranty lengths, a possible non-linear relationship have not been explored in the literature. More specifically, Kia offers warranties to cover factory-installed parts up to 5/60,000 (year/mileage) and power-train components up to 10/100,000, compared to its more reliable competitor Nissan, which offers 3/36,000 in basic warranties and 5/60,000 in power-train warranties. In contrast, warranties offered by Toyota are shorter in length (3/36,000 and 5/60,000 in basic and power-train) than those offered by its more reliable sibling Lexus (4/50,000 and 6/70,000). Plotting a scatter diagram using automobile producers' reliability scores from J. D. Power (see detail in section 4.3.1) and their warranty coverage in years (Figure 3.1), we observe that automobile producers seem to be offering longer warranties when the reliability of their vehicles is perceived to be either high or low.

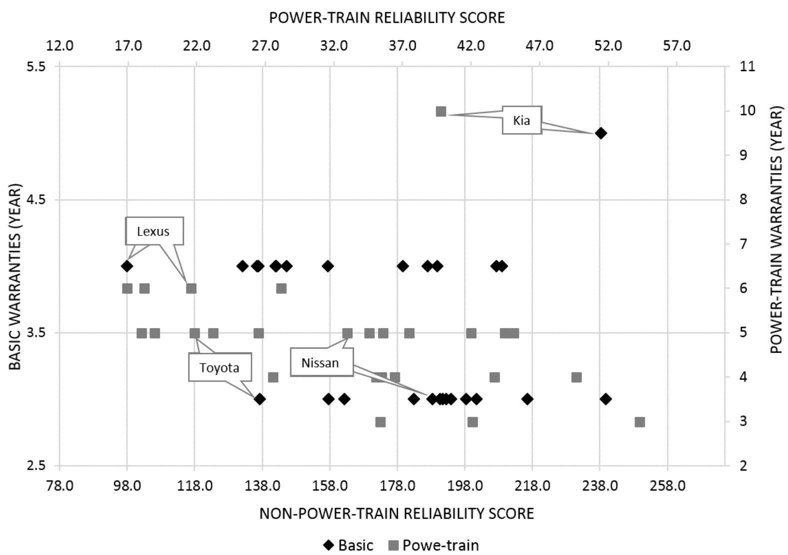

Figure 3.1: Product reliability and warranty length

The length of basic warranties in years with the non-power-train reliability score from J. D. Power's Vehicle Dependability Study are indicated by black diamonds. Since the score indicates the number of problems encountered per hundred vehicles, a lower score indicates a higher reliability. The length of power-train warranties in years with the power-train reliability score are marked by gray squares. All data are from 2008.

Although automobiles are certainly durable products, a characteristic key to the notion of a durable-goods market is the presence of consumer-to-consumer trading, i.e., secondary markets, remains yet unexplored in this context. More specifically, longer product warranties can help increase customers' valuation of products, but they may also affect the trading of used products, increase the cannibalization of new-product sales, and become detrimental to profit potentials. Meanwhile, the durable-goods literature suggests that producers could mitigate the cannibalization of new products and enhance their profitability by interfering with secondary markets through a variety of mechanisms (Hendel & Lizzeri 1999, Waldman 2004), including trade-ins or buy-back programs, that may also address the tension between the opposing effects induced by longer warranties. Interestingly, the automobile market has been known to practice these strategies actively (Hendel & Lizzeri 2002, Johnson & Waldman 2003, Rao *et al.* 2009).

Motivated by these observations in the automobile market, we question whether a producer's decision regarding warranty lengths is influenced by the presence of secondary markets and by its exercise of buy-back programs. Nevertheless, the implications of longer warranties in the presence of secondary markets and the interaction between warranty-length decisions and secondary market interference are unexplored in the literature. Therefore, our study takes the first step by formulating an analytical model to address these questions.

Following traditional and established market models in the durable-goods and recent operations management literature, our analytical model includes a profit-maximizing producer selling a product to a market with heterogeneous customers (Hendel & Lizzeri 1997, Huang *et al.* 2001, Agrawal *et al.* 2016, Alev *et al.* 2016). We incorporate product reliability, an attribute that affects customers' valuation of products and closely relates to the cost of servicing warranties, and endogenize a producer's decision on interfering with the market by exercising a buy-back program. To highlight the implications of the presence of secondary markets and the impact of the producer's secondary market interference, we identify the producer's optimal warranty-length decisions in three different scenarios: (i) without a secondary market, (ii) with a secondary market but no secondary market interference, and (iii) with secondary market interference, and examine the differences among them. The results show that the presence of secondary markets complicates the conditions under which the producer benefits from offering longer warranties: in the presence of secondary markets, the value of longer warranties is non-monotonic. We also find that the producer's secondary market interference further influences the conditions under which offering longer warranties is more profitable. Essentially, offering longer warranties can benefit two types of producers: as conventional wisdom has suggested, a producer observing low reliability in its products can leverage longer warranties to increase its profits. However, when interfering with a secondary market through exercising a buy-back program, a producer of reliable products may also benefit from longer warranties.

Our work provides several contributions to the literature. First, to our best knowledge, this study is the first to examine the implications of durable-goods warranty lengths in the presence of secondary markets. In particular, we highlight the trade-off between the increase in customers' product valuation and used-product cannibalization induced by a longer warranty. Second, we are also the first to explore the joint effect of producers' warranty-length decisions and their secondary market interference and reveal that the engagement in secondary market interference significantly changes the conditions under which offering longer warranties is more profitable. Third and most importantly, supported by our empirical findings in the next chapter, we offer a compelling explanation to durable-goods producers' decisions on the length of product warranties with respect to product reliability. For durable-goods producers, we highlight that the decisions regarding product warranty lengths are subtle because of the presence of secondary markets, and those making such decisions should also contemplate the decision of secondary market interference as well.

3.2 Literature Review

With a focus on a durable-goods producer's decision regarding the length of its product warranties and whether to interfere with the secondary market, we extensively reviewed two closely-related streams of research. The first is about the motives of warranties and their implications. The second is related to the durable-goods literature, focusing on the implications of the presence of secondary markets and producers' secondary market interference.

A large number of economics and marketing studies have examined the four economic rationales for offering product warranties: (i) an insurance effect, (ii) a signaling effect, (iii) an incentive mechanism, and (iv) a sorting mechanism. The insurance effect of warranties is about transferring potential loss caused by product breakdowns from customers back to producers (Heal 1977). The signaling effect suggests that warranties convey product reliability information unobservable to customers (Spence 1977, Kirmani & Rao 2000). The incentive stream regards warranties as a mechanism to incentivize producers to reveal and improve product reliability (Priest 1981, Cooper & Ross 1985). The sorting stream posits warranties as a marketing tool to segregate customers by their risk preference (Kubo 1986). Most of these studies emphasize market inefficiency (e.g., information asymmetry) and customer characteristics (e.g., heterogeneity in risk aversion). For a comprehensive review of these effects, please see Emons (1989) and Lutz (1996).

Empirical studies examining these warranty effects and their impact are few. Focusing on customers' valuation, Chu & Chintagunta (2008, 2011) examine these effects in the US automobile and personal computer markets and only find support to the insurance effect and the sorting effect, while providing some evidence that the failure rate of products and their warranty lengths are positively correlated. More recently, focusing on the US automobile market, Guajardo *et al.* (2016) regard warranty lengths as a service attribute and examine the relationships between warranty lengths, service quality, and product quality. They find that warranty lengths and service quality are complementary, and both compensate for product quality. That is, the value of a longer warranty is greater for a lower-quality product, which also supports the insurance effect.

Regarding producers' decisions on warranty lengths and their relationship with product reliability, Menezes & Currim (1992) propose an analytical model for the optimal product price and warranty length and suggest a negative relationship between product reliability and warranty length. However, they do not test the relationship. Instead, the authors assume that product prices and warranty lengths are exogenous, and empirically test their associations with sales. On the other hand, relying on the signaling stream of the warranty literature, several empirical studies examine the relationship between product reliability and warranty length and obtain mixed findings. Gerner & Bryant (1981) first find that warranties within a product category (e.g., TV, refrigerators, clothes dryers, and air conditioners) are highly standardized, and Priest (1981) find no connection between product life and warranty length. Both indicate that the link between product reliability and warranty length is insignificant. Using reliability measures from *Consumer Reports*, Wiener (1985) and Kelley (1988) each find a positive association between warranty length and product reliability in the appliance and automobile markets. Nevertheless, using a similar reliability measure from *Consumer Reports*, Douglas *et al.* (1993) find a negative association between warranty length and product reliability in the automobile market. They also find that the relationship becomes positive when they incorporate dealers' surcharges, which suggests that other factors may play a significant role in the relationship. Moreover, Agrawal & Richardson (1996) find no significant relationship after examining a range of electronic products and household appliances, and suggest exploring additional factors that may influence the relationship.

Our research thus attempts to fill the above gap by examining factors that have not been explored. That is, we examine the relationship with a focus on the two prominent characteristics observed in the automobile market: (i) the presence of secondary markets, a key notion of a durable-goods market, and (ii) producers' engagement in secondary market interference. In addition, we emphasize the insurance effect of warranties in the presence of secondary markets, and contribute to the literature by revealing additional implications of the effect.

The durable-goods literature has extensively examined the implications of the existence of secondary markets on producers' profitability. Since durable products could last a long time, they observe secondary markets. The resale value of used products in the secondary market positively affects the price of new products (Waldman 2003), but the availability of used products may substitute for demand for new products, which cannibalizes new-product sales and negatively contributes to producers' profits (Agrawal *et al.* 2016). Other studies in the stream have further suggested that producers may use strategies such as decreasing the availability of used products via planned obsolescence (Waldman 2003, Agrawal *et al.* 2016), buy-backs or trade-ins (Fudenberg & Tirole 1998, Rao *et al.* 2009), improving the value of used products through licensing or recertification programs (Oraiopoulos *et al.* 2012, Huang *et al.* 2016), or eliminating secondary market competition through leasing (Waldman 1997, Hendel & Lizzeri 1999). The underlying mechanism of these strategies is to influence the resale value of used products, hence adjusting the balance between the positive (resale value) effect and the negative (cannibalization) effect exerted by secondary markets (Oraiopoulos *et al.* 2012). Nevertheless, our understanding of the effect of warranties via the two opposing secondary market effects and the impact of secondary market interference, such as the popular trade-in/buy-back programs in the automobile market, is limited.

To the best of our knowledge, Utaka (2006) is one study that examines durable-goods producers' warranty decisions in the presence of a secondary market. Based on the signaling stream and using a three-period model, the study focuses on a monopolistic producer's moral-hazard problem and examines the implications of the producer's warranty decision (i.e., whether to offer warranties or repair services) on its product durability level and overall social welfare. The study endogenizes the value of used products but assumes exogenous demand for new products, which captures the positive secondary market effect but neglects the negative one. The author suggests that warranties can alleviate the moral-hazard problem and improve social welfare under an asymmetric information setting.

By revealing the non-monotonic benefit of offering longer warranties, we contribute to this stream of literature by highlighting the implications of the secondary market effects on a producer's warranty-length decision, a common but underexplored business decision for a durable-goods producer, as well as the impact of the producer's secondary market interference.

3.3 The Model

Focusing on a producer's decision regarding the warranty length of a product and the exercise of a buy-back program, we adopt the durable-goods model from Alev *et al.* (2016). This model is a discrete-time, infinite-horizon, and sequential game in which a profit-maximizing monopolistic producer produces a durable product and interferes with the secondary market through a buy-back program. In the following sections, we first describe the assumptions regarding the product, the customers, and the producer. We then outline the specification of the game.

3.3.1 The Product

We consider a durable product that has a two-period life span (Desai & Purohit 1998, Huang *et al.* 2001, Hendel & Lizzeri 1997, Agrawal *et al.* 2016) and depreciates with use. If the product has never been used, it is new and has a useful life of two periods. A used product has only one period of life remaining, and a depreciated value relates to a new product. A product after two-period use is referred to as end-of-life, and has no residual value. To indicate the characteristics relating to a new product and a used product, we introduce subscripts n and u, respectively. In addition, we assume the product is reliable, i.e., operating as its design specifies, to an extent. Motivated by market reliability indexes like the reliability score of J. D. Power's Vehicle Dependability Study, which measures the number of reliability related problems encountered by customers, we define f_n and f_u as the number of problems of a product during its first and second periods of use, and normalize them by the maximum number of problems (e.g., the number of components/features) such that $f_n \in (0, 1)$ and $f_u \in (0, 1)$. As such, $1 - f_n$ represents the new-product reliability (the extent of a new product meeting its original specifications), and $1 - f_u$ is the used-product reliability.

3.3.2 Customers

We assume that customers' valuation of a fully functional new product, θ, is heterogeneous and uniformly distributed in a market. In addition, we assume that the size of the market is one and stays constant. Thus, θ is $U[0, 1]$. As mentioned, customers have concerns regarding the reliability of products, and perceive a value depreciation on used products as $\delta \in (0, 1)$. As a result, a type θ customer perceives the value of using a new product as $(1 - f_n)\theta$ per period and the value of using a used product as $(1 - f_u)\delta\theta$ per period. The valuation of products reflects that consumers value the use of a new product more than the use of a used product in general[1], and the difference in valuation depends on product depreciation and reliability.

In this model, customers possess no more than one product in each time period. Therefore, at the beginning of a period, a customer can either buy a new product, buy a used product, keep their current product if it was new in the previous period, or stay inactive. In addition, if a secondary market exists, a customer who possesses a product with one period of useful life remaining may choose to sell the used product. Lastly, customers are forward-looking and have a value discount ρ per period.

3.3.3 The Producer

We assume that the producer is the only company that produces the product and offers warranties to customers. The producer chooses to offer product warranties in two different lengths, short (S) or long (L). Short warranties protect customers from reliability problems that may occur during the first period of product life, and long warranties protect customer for both periods of product life. Because both short and long warranties cover the first

[1] We assume $f_n \leq f_u$. That is, the reliability of new products equals or is better than that of used products

period of product life, the producer insures new-product customers from product breakdowns. Therefore, a type θ customer's valuation of using a new product increases from $(1 - f_n)\theta$ to θ. If the producer offers short warranties and provides no coverage to its used products, a type θ customer still values a used product at $(1 - f_u)\delta\theta$. That is, offering short warranties increases customers' valuation of new products but not that of used products. In contrast, if the producer offers long warranties, a type θ customer's valuation of a used product increases to $\delta\theta$. Nevertheless, the producer incurs an additional cost of servicing long warranties.

Assuming that the cost of administering warranties is negligible and that the cost of servicing a warranty increases with the number of reliability problems by a cost factor C_w, we have the warranty costs of a new product and a used product as $f_n C_w$ and $f_u C_w$, respectively. The warranty cost factor, C_w, represents the total cost of addressing possible reliability problems of a product. In addition, for ease in exposition, we denote the cost of producing a product (C_n) and servicing it in the first period ($f_n C_w$) as a baseline cost $\mathbb{C}$, i.e., $\mathbb{C} = C_n + f_n C_w$, and refer to the additional cost of servicing a used product as $f_u C_w$ when the producer chooses to offer long warranties.

We indicate time periods by t and use superscripts S and L to indicate variables when the producer offers short or long warranties. In a time period t, the producer prices a new product at $P_n^{S^t}$ if it offers short warranties or $P_n^{L^t}$ if it offers long warranties. In addition, if a secondary market exists, the producer may interfere with the secondary market by exercising a buy-back program. That is, the producer purchases some used products from the secondary market. We denote the quantities of buy-backs as $Q_u^{S^t}$ and $Q_u^{L^t}$ and refer to the prices of used products in the market as $P_u^{S^t}$ and $P_u^{L^t}$.

3.3.4 Specification of the Game

As mentioned, the game is a discrete-time, infinite-horizon, and sequential game. The producer makes the warranty-length decision, i.e., choosing a warranty length between short (S) or long (L), at the start of the game ($t = 0$). In each ensuing period $t > 0$, the producer makes the pricing decision, i.e., setting the price of new products in the chosen warranty length. If a secondary market exists, the producer also decides whether to interfere with the secondary market, i.e., determining the quantity of used products to buy back from the secondary market. After that, customers choose their actions to maximize their net present value. In addition, all information is common knowledge in this game and we solve the game by using backward induction.

3.4 Benchmark: No Secondary Market

While secondary markets exist for many durable products, they may be restrained by certain factors such as the lack of customer-to-customer trading infrastructure, substantial transaction costs, and regulatory restrictions. To better understand the impact of the presence of secondary markets, we examine a benchmark scenario in which no secondary market exists. We first characterize the demand for new products and represent the producer's problem. We then analyze the equilibria depending on the producer's warranty-length decision, and explore the producer's optimal warranty length.

3.4.1 Customer Strategies and Demand Functions

Because product life is two periods, we focus on two-period customer strategies. If the producer offers short warranties, the three two-period customer strategies are: (i) buying a new product and discarding it after one-period of use every period ($N^S N^S$); (ii) buying a new product and keeping the out-of-warranty used product ($N^S K^S$); and (iii) staying inactive always (II). Focusing on the stationary equilibrium of the game (Huang *et al.* 2001, Agrawal *et al.* 2016, Alev *et al.* 2016), we eliminate the time index in our notations, i.e., $P_n^{S^t} = P_n^S$, and identify the net present value of these respective strategies as: $\mathbb{V}_\theta[N^S N^S] = \frac{\theta - P_n^S}{1-\rho}$, $\mathbb{V}_\theta[N^S K^S] = \frac{(1+\rho(1-f_u)\delta)\theta - P_n^S}{1-\rho^2}$, and $\mathbb{V}_\theta[II] = 0$. In addition, because $\frac{\partial \mathbb{V}_\theta[N^S N^S]}{\partial \theta} > \frac{\partial \mathbb{V}_\theta[N^S K^S]}{\partial \theta} > 0$, we find $\theta_1^S = \frac{P_n^S}{1-(1-f_u)\delta}$ and $\theta_2^S = \frac{P_n^S}{1+\rho(1-f_u)\delta}$ such that customers with $\theta \in (\theta_1^S, 1]$ prefer strategy $N^S N^S$, customers with $\theta \in (\theta_2^S, \theta_1^S]$ prefer strategy $N^S K^S$, and customers with $\theta \in [0, \theta_2^S]$ choose to be inactive. We then can express the demand function of new products with short warranties as $Q_n^S(P_n^S) = 1 - \theta_1^S + \frac{1}{2}(\theta_1^S - \theta_2^S)$ and refer to the quantity of used products remaining in the market as $Q_k^S(P_n^S) = \frac{1}{2}(\theta_1^S - \theta_2^S)$.

If the producer offers long warranties, we identify the stationary equilibrium by setting $f_u = 0$ in the customer utility. More specifically, the net present values of customer strategies are $\mathbb{V}_\theta[N^L N^L] = \frac{\theta - P_n^L}{1-\rho}$, $\mathbb{V}_\theta[N^L K^L] = \frac{(1+\rho\delta)\theta - P_n^L}{1-\rho^2}$, and $\mathbb{V}_\theta[II] = 0$. Since $\frac{\partial \mathbb{V}_\theta[N^L N^L]}{\partial \theta} > \frac{\partial \mathbb{V}_\theta[N^L K^L]}{\partial \theta} > 0$ still, and the thresholds of these customer strategies are $\theta_1^L = \frac{P_n^L}{1-\delta}$ and $\theta_2^L = \frac{P_n^L}{1+\rho\delta}$, the demand for new products with long warranties is $Q_n^L(P_n^L) = 1 - \theta_1^L + \frac{1}{2}(\theta_1^L - \theta_2^L)$ and the quantity of used products remaining in the market is $Q_k^L(P_n^L) = \frac{1}{2}(\theta_1^L - \theta_2^L)$.

3.4.2 Producer's Problem

Under stationarity, we denote the per-period steady state profit of the producer offering short warranties as Π^S and reduce the profit-maximizing producer's problem to the steady-state objective function: $\max_{P_n^S} \Pi^S = Q_n^S(P_n^S)(P_n^S - \mathbb{C})$. If the producer offers long warranties, it incurs the additional cost of servicing long warranties, $Q_k^L(P_n^L) f_u C_w$. Therefore, the objective function becomes $\max_{P_n^L} \Pi^L = Q_n^L(P_n^L)(P_n^L - \mathbb{C}) - Q_k^L(P_n^L) f_u C_w$.

3.4.3 Equilibrium Analysis

We first note the price thresholds that influence market segmentation outcomes.

Lemma 3.1 *In the absence of the secondary market, a threshold in product price exists (i.e., $1-(1-f_u)\delta$ if the producer offers short warranties, or $1-\delta$ if the producer offers long warranties) such that a portion of customers discard their used products if the producer prices new products below the threshold.*

When the producer offers short warranties, we note that strategy $N^S N^S$ is active only if

$\theta_1^S < 1$ (when the producer offers long warranties, $N^L N^L$ is active only if $\theta_1^L < 1$). That is, if the price of a new product is sufficiently low, customers with higher product valuation (higher θ) may value the difference between a new product and a used product more than the price of a new product, resulting in the purchase of a new product and the discarding of a used product every period. We incorporate this threshold and solve the producer's problem by the Karush Kuhn-Tucker (KKT) approach if the producer offers short warranties, as well as if the producer offers long warranties.

Proposition 3.1 *In the absence of the secondary market, a threshold, $\widetilde{C_b^S}(\delta, f_u)(\widetilde{C_b^L}(\delta, f_u, C_w))$, exists such that the producer offering short (long) warranties adopts a different pricing policy when $\mathbb{C} < \widetilde{C_b^S}$ ($\mathbb{C} < \widetilde{C_b^L}$). That is, $P_b^{S*} = \frac{1+\mathbb{C}+(1-f_u)\delta}{2}$ when $\mathbb{C} \geq \widetilde{C_b^S}$ and $P_b^{S*} = \frac{1+\mathbb{C}-(1-f_u)^2\delta^2}{2}$ when $\mathbb{C} < \widetilde{C_b^S}$ ($P_b^{L*} = \frac{1+\mathbb{C}+\delta+f_u C_w}{2}$ when $\mathbb{C} \geq \widetilde{C_b^L}$ and $P_b^{L*} = \frac{1+\mathbb{C}-\delta^2-f_u C_w \delta}{2}$ when $\mathbb{C} < \widetilde{C_b^L}$).*

When the producer's baseline cost $\mathbb{C}$ is low, the producer can price new products below the price thresholds in Lemma 3.1 and, therefore, a portion of customers discard their used products. More interestingly, the pricing policies below the baseline cost thresholds indicates that the producer may drop the new-product price substantially at the thresholds ($\frac{(1+\delta)\delta(1-f_u)}{2}$ at $\widetilde{C_b^S}$ if the producer offers short warranties and $\frac{(1+\delta)(\delta+f_u C_w)}{2}$ at $\widetilde{C_b^L}$ if the producer offers long warranties). The reason for this is that customers' choice between purchasing a new product (and discarding a used product) every period or keeping a used product represents the competition between new and used products (i.e., potential cannibalization of new-product sales) and the producer prefers customers discarding their used products. As a result, when the producer can price new products low and lead customers to discard their used products, the producer may lower the price further to motivate more customers to discard their used products and reduce the cannibalization of new products at a greater extent.

3.4.4 Warranty Length Decision

We next explore the producer's warranty-length decision when the secondary market is absent. We compare the optimal profit if the producer offers short warranties and that if it offers long warranties to determine the producer's optimal warranty-length decision. We summarize our findings in Corollary 3.1.

Corollary 3.1 *Let* $\mathbb{C} \geq max(\widetilde{C_b^S}, \widetilde{C_b^L})$ *and* $C_w < \delta$. *At most one threshold,* f_B', *exists such that offering long warranties is more profitable when* $f_B' < f_u$.

Defining the profit margin of a new product if the producer offers short warranties as $P_b^{S*} - \mathbb{C}$, and that if the producer offers long warranties as $P_b^{L*} - \mathbb{C} - f_u C_w$, a higher baseline cost $\mathbb{C}$ of a product implies a lower profit margin. When $\mathbb{C} \geq max(\widetilde{C_b^S}, \widetilde{C_b^L})$, low profit margins prohibit the producer from lowing new-product prices and motivating customers to discard their used products. Thus, all customers keep used products. Notably, the difference between the profit margin of offering short warranties and that of offering long warranties is $f_u(\delta - C_w)$, and the condition $C_w < \delta$ implies that the additional cost of offering a long warranty is less than the increase in the used-product valuation it contributes. In addition, the difference increases linearly in f_u, indicating that the increase in the profit margin gained by offering long warranties becomes greater when the reliability of used products is lower. As such, when used-product reliability is low, offering long warranties increases the profit margin sufficiently, offsets the decrease in demand for new products induced by the increase in new-product price, and results in greater profits than offering short warranties. Figure 3.2 illustrates an example in which offering long warranties is more profitable when $f_u > f_B'$. The finding indicates that the value-added by offering long warranties is the preeminent factor in the warranty-length decision.[2]

[2]When $\mathbb{C} \leq min(\widetilde{C_b^S}, \widetilde{C_b^L})$, offering long warranties is always sub-optimal even if it is costless to do so, $C_w = 0$. This is because when producers can price their new products to have a portion of customers discard used products, producers may further lower the price to reduce the cannibalization of new products. As such, producers naturally prefer having used products valued less by offering short warranties.

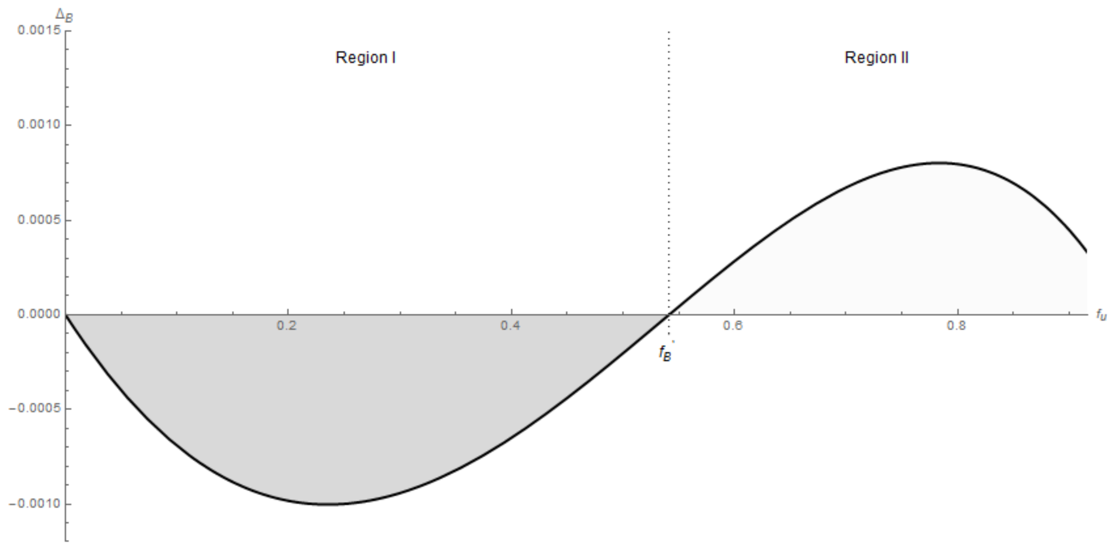

Figure 3.2: Profit difference when the secondary market is absent

$\delta = 0.6$, $\mathbb{C} = 1.05$, and $C_w = 0.55$. The bold line, Δ_B, represents the difference between the optimal profit if the producer offers short warranties and that if it offers long warranties. Δ_B is positive when offering long warranties is more profitable.

Proofs are shown in Appendix B.1. Corollary 3.1 reflects the conventional wisdom that durable-goods producers benefit from offering longer warranties when the reliability of their products is a concern. Nevertheless, this finding falls short of explaining the observed relationship between automobile producers' warranty lengths and their reliability scores. We next examine the implications of the presence of a secondary market.

3.5 Presence of a Secondary Market

Using an approach similar to that in the previous section, we characterize the demand for new products and represent the producer's problem in the presence of a secondary market. We first identify the equilibrium by the producer's warranty-length decision and investigate the implications of the used product reliability on these equilibria. We then examine the producer's warranty-length decision when it does not interfere with the secondary market. After that, we explore the impact of secondary market interference on the decision.

3.5.1 Customer Strategies

We assume that a secondary market exists and that transaction costs in the market are negligible. Following the intuitive argument in Hendel & Lizzeri (1997) that keeping a product is equivalent to selling a product and buying it back immediately, we reduce customer actions at the beginning of each period to: buying a new product with a short warranty and selling it to the secondary market after one-period use, buying an out-of-warranty used product, or staying inactive. As a result, if the producer offers short warranties, the three customer strategies that are un-dominated and could be active are: buying a new product with a short warranty every period ($N^S N^S$); buying an out-of-warranty used product every period ($U^S U^S$); and staying inactive always (II). The net present values of these customer strategies are: $\mathbb{V}_\theta[N^S N^S] = \frac{\theta - P_n^S + \rho P_u^S}{1-\rho}$; $\mathbb{V}_\theta[U^S U^S] = \frac{(1-f_u)\delta\theta - P_u^S}{1-\rho}$; and $\mathbb{V}_\theta[II] = 0$, respectively. In addition, because $\frac{\partial \mathbb{V}_\theta[N^S N^S]}{\partial \theta} > \frac{\partial \mathbb{V}_\theta[U^S U^S]}{\partial \theta} > 0$, we find thresholds $\theta_1^S = \frac{P_n^S - (1+\rho)P_u^S}{1-(1-f_u)\delta}$ and $\theta_2^S = \frac{P_u^S}{(1-f_u)\delta}$ such that customers with $\theta \in (\theta_1^S, 1]$ prefer strategy $N^S N^S$, customers with $\theta \in (\theta_2^S, \theta_1^S]$ prefer strategy $U^S U^S$, and customers with $\theta \in [0, \theta_2^S]$ choose to be inactive.

If the producer offers long warranties, the three customer strategies that could be active are: buying a new product with a long warranty ($N^L N^L$); buying an in-warranty used product every period ($U^L U^L$); and staying inactive always (II). We also identify the stationary equilibrium by eliminating f_u. That is, the net present values of these customer strategies are: $\mathbb{V}_\theta[N^L N^L] = \frac{\theta - P_n^L + \rho P_u^L}{1-\rho}$, $\mathbb{V}_\theta[U^L U^L] = \frac{\delta\theta - P_u^L}{1-\rho}$, and $\mathbb{V}_\theta[II] = 0$. Because $\frac{\partial \mathbb{V}_\theta[N^L N^L]}{\partial \theta} > \frac{\partial \mathbb{V}_\theta[U^L U^L]}{\partial \theta} > 0$, we also have thresholds $\theta_1^L = \frac{P_n^L - (1+\rho)P_u^L}{1-\delta}$ and $\theta_2^L = \frac{P_u^L}{\delta}$.

3.5.2 Demand Functions and Market-clearing Prices

At the stationary equilibrium, the number of customers who prefer new products is $Q_n^S(P_n^S, Q_u^S) = 1 - \theta_1^S$. These customers sell their products in the secondary market after one-period use. Meanwhile, the producer may purchase some used products back from the secondary market through a buy-back program. Assuming that used products are traded in the secondary market at a market-clearing price, which implies that the supply of used products equals the sum of the number of customers who prefer them and the quantity bought back by the producer, i.e., $Q_n^S(P_n^S, Q_u^S) = \theta_1^S - \theta_2^S + Q_u^S$. By solving these equations simultaneously, we can express the demand function of new products with short warranties as $Q_n^S(P_n^S, Q_u^S) = \frac{1+\rho(1-f_u)\delta+(1+\rho)(1-f_u)\delta Q_u^S - P_n^S}{1+(1+2\rho)(1-f_u)\delta}$. We also can derive the market clearing price of used products if the producer offers short warranties as $P_u^S(P_n^S, Q_u^S) = \frac{(1-f_u)\delta\left(2P_n^S-(1-(1-f_u)\delta)(1-Q_u^S)\right)}{1+(1+2\rho)(1-f_u)\delta}$. Both functions increase in Q_u^S, which implies that buying back used products improves the resale value of new products (Alev *et al.* 2016) and increases the demand for new products.

If the producer offers long warranties, we solve $Q_n^L(P_n^L, Q_u^L) = 1-\theta_1^L$ and $Q_n^L(P_n^L, Q_u^L) - Q_u^L = \theta_1^L - \theta_2^L$ together. We have the demand for new products with long warranties as $Q_n^L(P_n^L, Q_u^L) = \frac{1+\rho\delta+(1+\rho)\delta Q_u^L - P_n^L}{1+(1+2\rho)\delta}$ and the used-product market clearing price as $P_u^L(P_n^L, Q_u^L) = \frac{\delta\left(2P_n^L-(1-\delta)(1-Q_u^L)\right)}{1+(1+2\rho)\delta}$. Both functions also increase in Q_u^L. In addition, the demand functions under both warranty lengths, as well as the used-product prices, become the same if $f_u = 0$.

3.5.3 Producer's Problem

In the presence of the secondary market, the producer also determines the quantity of used products to buy back at the beginning of every period. If the producer offers short warranties, we reduce the producer's problem to the steady-state objective function: $\max_{P_n^S, Q_u^S} \Pi^S = Q_n^S(P_n^S, Q_u^S)(P_n^S - \mathbb{C}) - Q_u^S P_u^S(P_n^S, Q_u^S)$ s.t. $Q_n^S(P_n^S, Q_u^S) \geq Q_u^S \geq 0$, where $Q_u^S P_u^S(P_n^S, Q_u^S)$ is the total cost of buying back used products; the constraint $Q_n^S(P_n^S, Q_u^S) \geq Q_u^S$ ensures that the producer does not buy back more used products than they produce. If the producer offers long warranties, the objective function is $\max_{P_n^L, Q_u^L} \Pi^L = Q_n^L(P_n^L, Q_u^L)(P_n^L - \mathbb{C}) - Q_u^L P_u^L(P_n^L, Q_u^L) - (Q_n^L(P_n^L, Q_u^L) - Q_u^L) f C_w$ s.t. $Q_n^L(P_n^L, Q_u^L) \geq Q_u^L \geq 0$, where $(Q_n^L(P_n^L, Q_u^L) - Q_u^L) f C_w$ is the additional cost of servicing longer warranties on products that remain in the market.

3.5.4 Equilibrium Analysis

We also solve the producer's problems by the Karush Kuhn-Tucker (KKT) approach and highlight the conditions under which the producer interferes with the secondary market in Proposition 3.2.

Proposition 3.2 *If the producer offers short warranties, the producer exercises a buy-back program ($Q_u^{S*} > 0$) when $2\mathbb{C} + (1 - f_u)\delta \leq 1$. If the producer offers long warranties, the producer exercises a buy-back program ($Q_u^{L*} > 0$) when $2\mathbb{C} + \delta \leq 1 + \frac{1+\delta}{\delta} f_u C_w$. In addition, if the producer offers long warranties and $\mathbb{C}\delta \leq C_w f_u$, the producer shuts down the secondary market ($Q_n^{L*}(P_n^{L*}, Q_u^{L*}) = Q_u^{L*}$).*

Proof of Proposition 3.2: see Appendix B.2. ■

If the producer offers short warranties, it is not responsible for the reliability issues of used products. Therefore, the condition of exercising a buy-back program is independent of the warranty cost factor C_w. Notably, for a perfectly reliable used product ($f_u = 0$), the condition of the partial buy-back policy is the same as that in Lemma 1 of Alev *et al.* (2016), which suggests that durable-goods producers may interfere with the secondary market by exercising a buy-back program when the profit margin or the depreciation of their products is high. We can also infer that because the decrease in used-product valuation makes buying back programs more affordable, producers are more likely to exercise a buy-back program when they observe lower used-product reliability.

We refer to the solution in which buying back used products from the secondary market is suboptimal as the "no buy-back policy ($Q_u^{S*} = 0$ or $Q_u^{L*} = 0$)" and the solution in which the producer may buy back some used products as the "partial buy-back policy ($Q_u^{S*} > 0$ or $Q_u^{L*} > 0$)". As also found in Alev *et al.* (2016), a policy under which the producer buys back all used products and shuts down the secondary market completely, i.e., $Q_n^{S*}(P_n^{S*}, Q_u^{S*}) = Q_u^{S*} > 0$, is always suboptimal if the producer offers short warranties.

If the producer can offer long warranties at no cost ($C_w = 0$), the condition of the partial buy-back policy also becomes the same as that in Lemma 1 of Alev *et al.* (2016). This condition also implies that producers are more likely to exercise a buy-back program if the additional cost of servicing its long warranty ($C_w f_u$) is higher. That is, if a producer offers long warranties, buying back used products also reduces its obligation to service in-warranty used products.

Interestingly, if the producer offers long warranties, the "full buy-back policy ($Q_n^{L*}(P_n^{L*}, Q_u^{L*}) = Q_u^{L*} > 0$)" is viable. The condition of this policy indicates that if the profit margin of the product is high, if the depreciation of the product is high, or if the additional warranty cost is substantial, shutting down the secondary market completely is optimal. The finding also suggests that because of the additional savings from reducing the number of in-warranty used products in the market, durable-goods producers may shutdown the secondary market if they offer long warranties.

To better understand the implications of the presence of the secondary market and the producer's secondary market interference and to shed light on the factors that influence the warranty-length decision, we further examine these equilibria with respect to used-product reliability. For ease of exposition, we define buy-back policy thresholds in used-product reliability as $\overline{f_{NN}} = \min[\frac{2\mathbb{C}-1+\delta}{\delta}, \frac{\delta(2\mathbb{C}-1+\delta)}{(1+\delta)C_w}]$, $\underline{f_{PP}} = \max[\frac{2\mathbb{C}-1+\delta}{\delta}, \frac{\delta(2\mathbb{C}-1+\delta)}{(1+\delta)C_w}]$, $\overline{\overline{f^L}} = \frac{\mathbb{C}\delta}{C_w}$ such that the no buy-back policy is optimal when $f_u < \overline{f_{NN}}$ regardless of the producer's warranty-length decision, that the partial buy-back policy is always optimal when $\underline{f_{PP}} < f_u < \overline{\overline{f^L}}$, and that if the producer offers long warranties, the full buy-back policy is optimal when $f_u > \overline{\overline{f^L}}$. If the used-product reliability is sufficiently low ($f_u > \overline{f_{NN}}$), durable-goods producers may find interfering with the secondary market is more profitable. In addition, we note that $\underline{f_{PP}} < 0$ when $2\mathbb{C} + \delta < 1$, indicating that the producer may interfere with the secondary market when the profit margin and the depreciation of the product are sufficiently high, regardless of the warranty-length decision. We then summarize our findings in Corollary 3.2.

Corollary 3.2 P_n^{S*} *and* P_n^{L*} *are the same as that in the no secondary market scenario* *when customers keep used products. They are also consistent under the no buy-back policy and the partial buy-back policy.*

Let $\overline{f_{NN}} < 1$*, i.e., a buy-back policy is optimal when used-product reliability is sufficiently low, and* $C_w < \delta$*. For used-product reliability such that the no buy-back policy is optimal,*
(i) $Q_n^{S*}(P_n^{S*}, 0)$ *is increasing and convex in* f_u*,*
(ii) and $Q_n^{L*}(P_n^{L*}, 0)$ *is decreasing linearly in* f_u*.*
For used-product reliability such that the partial buy-back policy is optimal,
(iii) Q_u^{S*} *and* $Q_n^{S*}(P_n^{S*}, Q_u^{S*})$ *are both increasing and concave in* f_u*,*
(iv) and Q_u^{L*} *and* $Q_n^{L*}(P_n^{L*}, Q_u^{L*})$ *are both increasing linearly in* f_u*.*

The optimal pricing policies, depending on the producer's warranty-length decision, are identical to those when the secondary market is absent and customers keep used products. They are also consistent under the no buy-back policy and the partial buy-back policy. Therefore, as noted in the no secondary market scenario, the value-added by offering long warranties increase linearly as the reliability of used products decreases.

Regarding the optimal production and buy-back quantities, we focus on the condition $\overline{f_{NN}} < 1$ under which interfering with the secondary market is more profitable when the used-product reliability is low.[3] When the no buy-back policy is optimal and if the producer offers short warranties (i), a decrease in used-product reliability reduces the new-product price and decreases the cannibalization of new products. Both increase demand for new products. If the producer offers long warranties (ii), customers' valuation of products is ensured and the producer demands a higher price when it observes lower used-product reliability, resulting in less demand for new products. When exercising a buy-back program is optimal, a decrease in used-product reliability leads to a greater extent of buy-back activities. If the producer offers short warranties (iii), a decrease in used-product reliability

[3]When $\overline{f_{NN}} > 1$, i.e., the no buy-back policy is always optimal regardless of the producer's warranty length decision, the optimal warranty-length decision is also a threshold policy similar to that when the secondary market is absent and all customers keep used products (detail available upon request).

decreases used-product valuation, and the producer can afford to buy more used products. Nevertheless, as a decrease in used-product reliability also reduces the cannibalization of new products, it limits the efficacy of the buy-back program. As a result, if the producer observes lower used-product reliability, it increases buy-back activities but at a lesser rate. If the producer offers long warranties (iv), the warranty coverage of used products protects the value of used products and ensures the efficacy of the buy-back program. Nevertheless, in this context, producers may completely remove used products from the secondary market if their used-product reliability is sufficiently low.

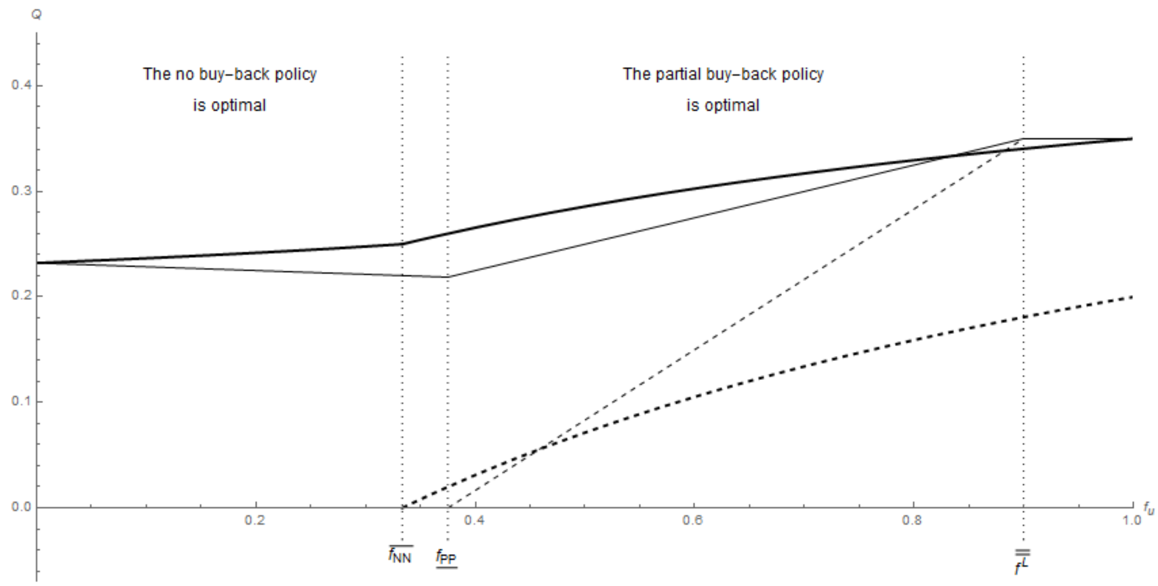

Figure 3.3: The optimal production and buy-back quantities

$\delta = 0.6$, $\mathbb{C} = 0.3$, and $C_w = 0.2$. The solid bold line represents the optimal production quantities when the producer offers short warranties Q_n^{S*} and the dashed bold line is the corresponding optimal buy-back quantities Q_u^{S*}. The solid thin line is the optimal production quantities when the producer offers long warranties Q_n^{L*} and the dashed thin line is the corresponding optimal buy-back quantity Q_u^{L*}.

Figure 3.3 illustrates the findings in Corollary 3.2 and the positions of these buy-back policy thresholds. In the region between $\overline{f_{NN}}$ and $\underline{f_{PP}}$, different buy-back policies are optimal depending on the producer's warranty-length decision. In addition, the region where $f_u > \overline{\overline{f^L}}$ indicates that the producer may shut down the secondary market if it offers long warranties.

3.5.5 Warranty Length Decision

We first explore a scenario in which the no buy-back policy is optimal regardless of the producer's warranty-length decision, and examine the optimal warranty length decision by comparing the optimal profit if the producer offers short warranties and that if it offers long warranties. We summarize our findings in Corollary 3.3.

Corollary 3.3 *Let $f_u < \overline{f_{NN}}$, i.e., the buy-back policies are sub-optimal, and $C_w < \delta$. At most two thresholds, f'_{NN}&f''_{NN}, exist such that offering long warranties is more profitable when $f'_{NN} < f_u < f''_{NN}$.*

Proof of Corollary 3.3: see Appendix B.3. ■

Figure 3.4 illustrates an example in which both thresholds exist. The finding suggests that durable-goods producers are more likely to offer longer warranties when their used-product reliability is in the middle ($f'_{NN} < f_u < f''_{NN}$ and region II in Figure 3.4).

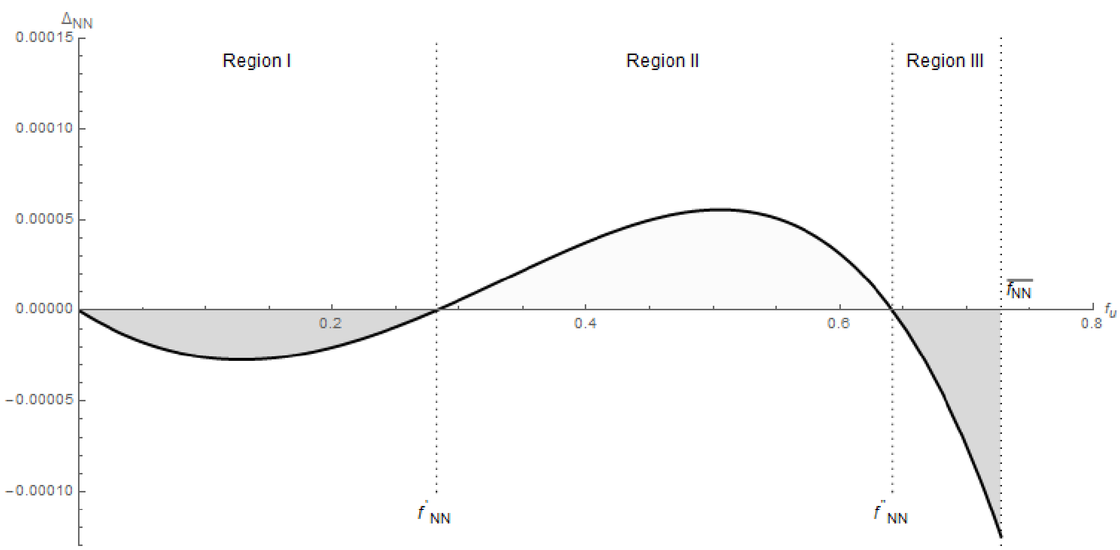

Figure 3.4: Profit difference when the no buy-back policy is optimal

$\delta = 0.55$, $\mathbb{C} = 0.435$, and $C_w = 0.205$. The bold line, Δ_{NN}, represents the difference between the optimal profit if the producer offers short warranties and that if it offers long warranties under the no buy-back policy. Δ_{NN} is positive when offering long warranties is more profitable.

Because the value-added by offering long warranties is greater when the reliability of used products is lower, the condition $f_u < f'_{NN}$ indicates that when used products are sufficiently reliable, the increase in the profit margin by offering long warranties is insufficient to offset the decrease in demand for new products induced. In contrast, $f_u > f'_{NN}$ indicates that when the used products are less reliable, the increase in the profit margin by offering long warranties becomes sufficient. The rationale for threshold f'_{NN} is similar to that for threshold f'_B (and Region I & II in Figure 3.2) in the benchmark scenario. More specifically, in this context, the value-added by offering long warranties via the resale value effect is the predominant factor in the warranty-length decision.

Threshold f''_{NN} highlights the difference in the warranty-length decision because of the presence of a secondary market. As noted by comparing Corollary 3.2 (i) to (ii), the difference between the optimal production quantity if the producer offers short warranties and that if the producer offers long warranties is increasing and convex in f_u. That is, as the reliability of used products gets lower, offering long warranties increases the cannibalization of the new-product market at a greater rate. Therefore, the condition $f_u > f''_{NN}$ (and Region III in Figure 3.4) indicates that when used products are unreliable, offering long warranties induces substantial cannibalization of new products. The producer is more profitable by offering short warranties to protect its new-product market. In other words, the cannibalization effect induced by the added value of long warranties becomes the preeminent factor in the warranty-length decision.

Corollary 3.3 shows that the value-added by offering long warranties influences the balance between the secondary market effects (i.e., the positive resale-value effect and the negative cannibalization effect), resulting in the observed non-monotonic benefit of offering long warranties. Durable-goods producers that do not engage in secondary market interference are more likely to offer long warranties when their used products are less reliable, but they reverse the decision when their used products are unreliable. In addition, this finding indicates that the producer's warranty-length decision is more sensitive and flexible than the decision to interfere with the secondary market. That is, when durable-goods producers are concerned about the used-product cannibalization, although they may not yet be able to exercise a buy-back program to mitigate the concern (e.g., because of an insufficient profit margin), they may nonetheless change their warranty lengths.

We next examine a scenario in which buying back used products is optimal regardless of the producer's warranty-length decision,[4] and explore the impact of the producer's secondary market interference on its warranty-length decision. We summarize the optimal decision of the producer's warranty length in Corollary 3.4.

Corollary 3.4 *Let* $\underline{f_{PP}} < f_u < \overline{\overline{f_L}}$*, i.e., the partial buy-back policy is optimal, and* $\overline{\overline{f_L}} > 1$*. At most two thresholds,* $f'_{PP}\&f''_{PP}$*, exist such that offering long warranties is more profitable when* $f_u < f'_{PP}$ *or when* $f_u > f''_{PP}$*.*

Proof of Corollary 3.4: see Appendix B.5. ■

We focus on the condition that the full buy-back policy is never optimal even if the producer offers long warranties, i.e., $\overline{\overline{f_L}} > 1$. Figure 3.5 illustrates an example in which both thresholds exist under these conditions. Different from Corollary 3.3 in the previous scenario, Corollary 3.4 suggests that when durable-goods producers engage in secondary market interference and never shut down the secondary market, they are more likely to offer longer warranties when their used-product reliability is near an extreme, i.e., either low or high ($f_u < f'_{PP}$ or $f_u > f''_{PP}$, and region I & III in Figure 3.4).

The condition, $\underline{f_{PP}} < 1$ and $\overline{\overline{f_L}} > 1$, implies that $C_w < \frac{\delta}{2}$, which is more stringent than the condition of having positive value-added by offering long warranties, $C_w < \delta$. A smaller warranty cost factor indicates a more substantial added value of long warranties, resulting in the greater profitability of offering long warranties when $f_u < f'_{PP}$ (region I in Figure 3.5). Nevertheless, offering long warranties becomes less profitable when $f_u > f'_{PP}$, and the rationales for the threshold (and Region II in Figure 3.5) are twofold: the secondary market cannibalization and the limited efficacy of a buy-back program. The cannibalization

[4]We note that under conditions where the full buy-back policy is optimal when the producer offers long warranties, the producer is more profitable by offering short warranties. See Appendix B.4. Therefore, we focus on the condition where the partial buy-back policy is optimal, regardless of the producer's warranty-length decision

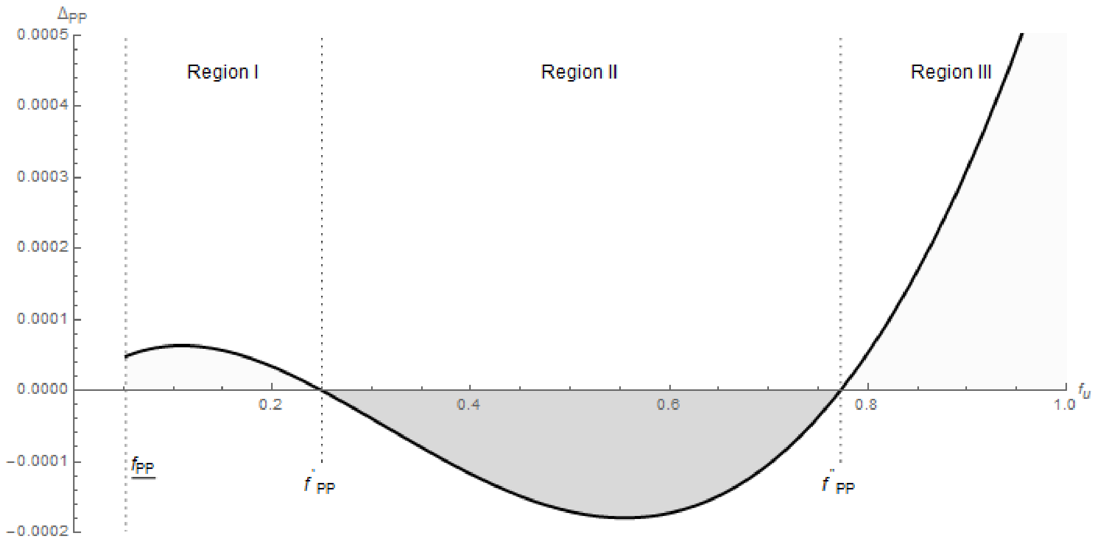

Figure 3.5: The profit difference when the partial buy-back policy is optimal

$\delta = 0.40$, $\mathbb{C} = 0.309$, and $C_w = 0.098$, which implies $\overline{\overline{f_L}} > 1$. The bold line, Δ_{PP}, represents the difference between the optimal profit if the producer offers short warranties and that if it offers long warranties under the partial buy-back policy. Δ_{PP} is positive if offering long warranties is more profitable.

of new-product market increases at a greater rate as the used-product reliability gets lower, which is the same rationale for threshold f''_{NN} (and region II & III in Figure 3.4) in the previous scenario. Meanwhile, as mentioned in Corollary 3.2 (iii) and (iv), because offering long warranties increases used-product valuation and makes the buy-back program more costly, the producer can afford to buy back fewer used products from the market and reduce the used-product cannibalization at a lesser extent. Therefore, offering long warranties may become less profitable when used products are less reliable, and the cannibalization effect of the secondary market and the efficacy of secondary market interference are the two preeminent factors.

The rationales for threshold f''_{PP} (and Region III in Figure 3.5) are likewise twofold: the improved efficacy of the buy-back program and the additional cost savings. As mentioned in Corollary 3.2 (iii) and (iv), if the producer offers short warranties, leveraging a buy-back program to address the used-product cannibalization becomes less effective as the used-product reliability decreases. The efficacy of the buy-back program remains consistent if the producer offers long warranties. As a result, when the producer's used-product reliability is sufficiently low, the buy-back program may become more effective if the producer offers long warranties than if the producer offers short warranties. Meanwhile, as noted from the condition of the partial buy-back policy if the producer offers long warranties in Proposition 3.2, offering long warranties and interfering with the secondary market jointly generates additional cost savings because a buy-back program removes in-warranty products from the market. As such, offering long warranties may become more profitable when used products are unreliable, and the efficacy of secondary market interference and the warranty-cost savings are the leading factors.

We further note that under the condition of $\overline{\overline{f_L}} < 1$ (e.g., the warranty cost factor is not small, or the product depreciation is high), f''_{PP} always > 1. As a result, the producer's warranty-length decision is a threshold policy, and offering long warranties is more profit only if $f_u < f'_{PP}$. This finding suggests that if a producer were to offer long warranties and shut down the secondary market when its used products are unreliable, the producer may offer long warranties only if its used products are sufficiently reliable .

Compared to the findings of Corollary 3.3 about durable-goods producers not interfering with the secondary market, the findings of Corollary 3.4 reveals several important insights regarding producers engaging in secondary market interference. First, when producers may be more profitable by engaging in secondary market interference, the added value of longer warranties is substantial, and they are more likely to offer long warranties. Nevertheless, the efficacy of producers' buy-back programs influence their warranty-length decision. Also, buy-back programs generate additional warranty-cost savings if producers offer long warranties. The interaction of these effects results in the non-monotonic benefit of offering long warranties. Second, producers' secondary market interference dramatically changes the conditions under which offering longer warranties is more profitable. More specifically, when producers do not interfere with the secondary market, offering longer warranties may be more profitable when the reliability of their used products is neither too high nor too low (i.e., less reliable but not unreliable). When producers actively engage in secondary market interference, offering longer warranties becomes more profitable when the reliability of their used products is either high or low (i.e., sufficiently reliable or unreliable). Third and most importantly, the findings offer a compelling explanation of our observations in the automobile market.

3.6 Conclusions

Many, if not all, durable goods come with product warranties. Nevertheless, our understanding of producers' decisions on their product warranty lengths, particularly on their relationship with product reliability, remains limited. In addition, while secondary markets exist for most durable products, to the best of our knowledge, our study is the first to examine producers' warranty-length decisions with respect to the reliability of their used products in the presence of secondary markets.

By analytically examining a durable-goods producer's optimal warranty-length decision in three different scenarios: (i) without a secondary market, (ii) with a secondary market but no secondary market interference, and (iii) with secondary market interference, we identify the implications of the presence of the secondary market and the impact of the producer's secondary market interference on its warranty-length decision. We first find that the value-added by longer warranties (via the resale-value effect when the secondary market presents) is consistent in all three scenarios. That is, offering longer warranties increases profit margins to a greater extent when used products are less reliable. In the presence of a secondary market, we find that the benefit of longer warranties becomes non-monotonic. Because the used-product cannibalization may emerge as the preeminent factor, producers become less likely to offer longer warranties when their used products are unreliable. When producers may engage in secondary market interference through a buy-back program to address the used-product cannibalization and increase profits, they are also more likely to offer longer warranties. Because of the used-product cannibalization and the limited efficacy of producers' buy-back programs, producers become less likely to offer longer warranties when their used products are less reliable. Nevertheless, the warranty-cost savings and the improved efficacy of secondary market interference increase the profitability of offering longer warranties when used products are unreliable. These findings, in general, support the conventional wisdom that producers may benefit from offering longer warranties when they concern their product reliability. They suggest that producers engaging in secondary market interference are more likely to offer longer warranties when their used products are sufficiently reliable.

We would like to note some of the limitations of our analytical model. First, as mentioned, our model is insufficient to address a product containing multiple components with disproportional cost. Second, our model assumes that information is public, which eliminates potential warranty effects such as that warranties can address the adverse selection problem (the lemon problem) in secondary markets caused by asymmetrical information. Third, our model considers a monopolistic producer, while an effect of warranties is to sort customers by their risk preference, which could play a strategic role in competition within used products. Future research can expand to these areas.

Nonetheless, our study contributes to the literature by incorporating the effects of secondary markets (the resale value effect and the cannibalization effect) in examining durable-goods producers' warranty-length decisions. In particular, we highlight the trade-off between the increase in customers' valuation and used-product cannibalization induced by offering longer warranties. By exploring the joint effect of producers' warranty-length decisions and their secondary market interference, we also show that the engagement in secondary market interference changes the balance between these secondary market effects and introduces an additional effect (the warranty-cost savings), resulting in significant changes to the conditions under which offering longer warranties is more profitable. More importantly, with these analytical findings, we set out to examine durable-goods producers' warranty-length decisions empirically.

CHAPTER 4
EMPIRICAL TESTS OF PRODUCT RELIABILITY ON PRODUCT WARRANTY LENGTHS AND SECONDARY MARKETS

4.1 Introduction

In this chapter, we conduct an empirical study that tests some of the insights coming out of our theoretical model in the previous chapter. Specifically, we test three predicted relationships from our theoretical model: (i) warranty length and product reliability, (ii) extent of buybacks and product reliability, and (iii) volume of trade in the secondary market and product reliability. Linking several secondary data sources regarding the US automobile market and applying the exploratory factor analysis and the panel-data analysis, we find evidence that automobile producers provide longer warranties, particularly no-power-train related warranties, when their used-vehicle reliability is near an extreme, i.e., either low or high. In addition, we show that automobile producers' buy-back activities decrease with the reliability of their used vehicles while the trade volume of their used vehicles increases with the reliability of used vehicles. Both are in line with our analytical predictions.

4.2 Empirical Context and Hypotheses

We choose the automobile industry as the context for our empirical study. Beyond the growing attention devoted to the warranty lengths and after-sale service qualities in this industry (Guajardo *et al.* 2016, Rao *et al.* 2009, Menezes & Currim 1992), it is also an appropriate setting for our analysis for several reasons. First, automobiles are certainly durable products, depreciate in use, and have active secondary markets. Second, automobile producers actively engage in secondary market strategies such as trade-ins and buy-back programs (Hendel & Lizzeri 2002, Johnson & Waldman 2003), which yields an ideal setting to study the interaction between producers' warranty and buy-back decisions, and volume of trade in secondary markets. Third, automobile producers commonly offer product warranties that vary in coverage and change periodically, which allows us to explore the reasons behind the variation in warranty decisions across producers.

There are also several context-specific factors that map some of the assumptions in our analytical model. The average age of vehicles sold on the secondary market is 4.4 years (Edmunds.com Inc. 2015) while the average life of automobiles is documented to be 10 years with the vehicle ownership data of Consumer Expenditure Survey. Our model approximates this observation with the use of a durable product that lasts for two periods. Furthermore, the average length of basic warranties is 3.6 years and that of power-train warranties is 5.2 years (based on warranty choices observed from our JL Warranty data). This indicates that automobile producers offer product warranties to cover at least the first period of product life, and that the timing of reselling a product coincides with the expiration of warranties to an extent. Moreover, warranty coverage is consistent among vehicle models, which allows us to examine producers' warranty-length decisions using an analytic model with a single product.

Corollary 3.4 suggests that a producer, which buys back some of its products from the secondary market, will offer longer warranties when the reliability of their used products are sufficiently low or high. Intuition suggests that while a producer may offer longer warranties to compensate the perceived loss in valuation of their products due to reliability concerns, the producer should be wary about the cannibalization induced by offering longer warranties when their used products are less reliable. Hence, a producer can safely offer longer warranties when its used products are highly reliable. As for a producer with unreliable used products, the producer would not need to worry about the cannibalization as the low used-product valuation eases the cannibalization of new products, and the producer would also enjoy additional cost savings from longer warranties by collecting in-warranty used products. Accordingly, we empirically test the following hypothesis:

Hypothesis 4.1 *The association between a producer's used-vehicle reliability and its warranty length is curvilinear (U-shaped).*

The third and fourth items of Corollary 3.2 suggest that a producer's optimal buy-back quantities decreases in the perceived reliability of its used cars, regardless of the producer's warranty length decision (i.e., $\frac{\partial Q_u^{S*}}{\partial f_u} > 0$ and $\frac{\partial Q_u^{L*}}{\partial f_u} > 0$). The same theoretical prediction holds when we measure buy-back volume in terms of the ratio of buy-back quantities to the corresponding production quantities (i.e., $\frac{Q_u^{S*}}{Q_n^{S*}}$ and $\frac{Q_u^{L*}}{Q_n^{L*}}$). Intuition suggests that less reliable used products have lower valuation, thereby making buybacks more affordable for producers. In addition, as offering longer warranties increases the valuation of less-reliable used products more, it increases cannibalization and promotes producers to buy back to a greater extent. Accordingly, we empirically test the following hypothesis:

Hypothesis 4.2 *The extent of buy-backs is negatively associated with a producer's used-vehicle reliability.*

We also empirically document the association between the volume of trade of a producer's used vehicles and their reliability. The quantity of used products remaining in the secondary market if the producer offers short warranties is $Q_n^{S*} - Q_u^{S*} = \frac{\mathbb{C}}{2(1-(1-f_u)\delta)}$, and that if the producer offers long warranties is is $Q_n^{L*} - Q_u^{L*} = \frac{\delta\mathbb{C} - f_u C_w}{2\delta(1-\delta)}$. For both cases, the remaining used-product quantities decrease in f_u. Intuitively, as producers buy back more used products when used products are less reliable, customer-to-customer trade volume is expected to decrease. Consequently, we test the following hypothesis:

Hypothesis 4.3 *Trade volume in the secondary market is positively associated with a producer's used-vehicle reliability.*

4.3 Data, Measures, and Empirical Approach

4.3.1 Data

We obtained secondary data regarding the US automobile market from several sources. The first is the Vehicle Dependability Study (VDS) from J. D. Power; the second is the Consumer Expenditure Survey (CES) administrated by the US Bureau of Labor Statistics (BLS); and the third is the detailed coverage information of manufacturing warranties collected by JL Warranty.

Vehicle Dependability Study. J. D. Power conducts the VDS for vehicle models annually and publishes their reliability scores. We chose this data because of its focus on long-term dependability of vehicles after extensive use, and its broad use in measuring used-vehicle reliability (NADA 2015, U.S. News & World Report 2016). To focus on long-term reliability, VDS specifically surveys vehicle owners who have had a given vehicle for three years. For example, for the 2013 VDS, J. D. Power selected a sample of owners who registered their vehicles from September 2009 to February 2010 to maintain the ownership period around three years. The study interviews these three-year original owners regarding problems they encountered during the most recent year in nine different attributes such as interior, HVAC (heating, ventilation, and air conditioning), and transmission. In addition, VDS surveys problems related with breakdowns or malfunctions of a component or a feature. These cover reliability-related issues such as a component or a feature that functions as designed but is difficult to use. J. D. Power uses the average number of problems per hundred vehicles (PP100) of a model as the model's reliability score. Hence, a lower score indicates a more reliable model. J. D. Power also publishes the reliability score of automobile producers, which weights the PP100 of a model of a producer by the sales of the model to the total sales of the producer and then sums up the weighted PP100 as the producer's reliability score.

Consumer Expenditure Survey. The BLS administrates two surveys in CES: the interview survey and the diary survey quarterly. From a representative sample of the US population, the interview survey captures the demographics, income, and asset information of each consumer unit (household) and its major expenditures. The diary survey records daily minor expenses and activities. The BLS then publishes public-use microdata that combine the raw data collected in both surveys annually. For the purposes of this study, we explore detailed responses related to vehicle ownership and transaction information of each household in the interview survey.

Warranty Coverage in the Automobile Market. In the US automobile market, automobile producers sell new vehicles with product warranties (also known as manufacturer warranties). Warranties are in various types including basic, power-train, and corrosion, with coverage limits in time and mileage explicitly stated. In general, these warranties are free of charge and mutually exclusive. In addition, producers may also offer warranties covering components for emission control or the battery of hybrid vehicles. Nevertheless, these three types of warranties, basic, power-train, and corrosion, are commonly offered by all producers. A basic warranty covers factory-installed parts and some dealer-installed accessories against defects and workmanship; a power-train warranty covers major power components such as engine, transmission, and differential drive shaft assembly; and a corrosion warranty covers rust-through perforation on sheet metal. JL Warranty, a company focusing on warranty claim processing in the automotive industry, collects the detailed coverage of producers' warranties and publishes the Official Warranty Guide annually, from where we extract the coverage of all three types of warranties in time and mileage.

4.3.2 Measures

Since a producer's warranties are consistent among its models, we have producer-year as our unit of analysis. Below we describe our measures in detail.

Warranty Lengths: As mentioned, automobile producers commonly offer product warranties in six aspects: the coverage of basic warranties in year and mileage, the coverage of power-train warranties in year and mileage[1], and the coverage of corrosion warranties in year and mileage. For the sake of parsimony, we first perform an exploratory factor analysis to examine the key factors underlying automobile producers' warranties.

Table 4.1: Factor loadings of automobile producers' 2008 warranty coverage

Variables	Factor 1	Factor 2
The coverage of basic warranties in year	0.9357	0.00920
The coverage of basic warranties in mileage	0.9346	0.1012
The coverage of power-train warranties in year	0.1544	0.8696
The coverage of power-train warranties in mileage	-0.0226	0.7191
The coverage of corrosion warranties in year	0.5229	-0.1078
The coverage of corrosion warranties in mileage	0.4016	0.4137

Notes: The pattern matrix from the orthogonal varimax rotation.

The factor analysis reveals that two key factors explain automobile producers' warranties (see Table 4.1). Although the interpretation of the resulting factors is a concern when using factor analysis, our result has a clear interpretation. The first factor strongly relates to the coverage of non-power-train warranties, whereas the second key factor represents the coverage of power-train specific warranties. The scatter plot of resulting scores by producers (Figure 4.1) further highlights distinctive characteristics in producers' warranty-length decisions. Some automobile producers like Kia, Lexus, and Smart have their warranties positively correlated between the two key factors, whereas producers like BMW, Volvo, and Suzuki seem to have their warranties negatively correlated between the two factors.

More importantly, the finding indicates that producers' decisions on non-power-train-

[1]The power-train warranties of Kia and Hyundai are partially transferable. Therefore, we use the transferable portion of their warranties in our analysis. Nevertheless, our results remain unchanged if we use the original coverage of their warranties

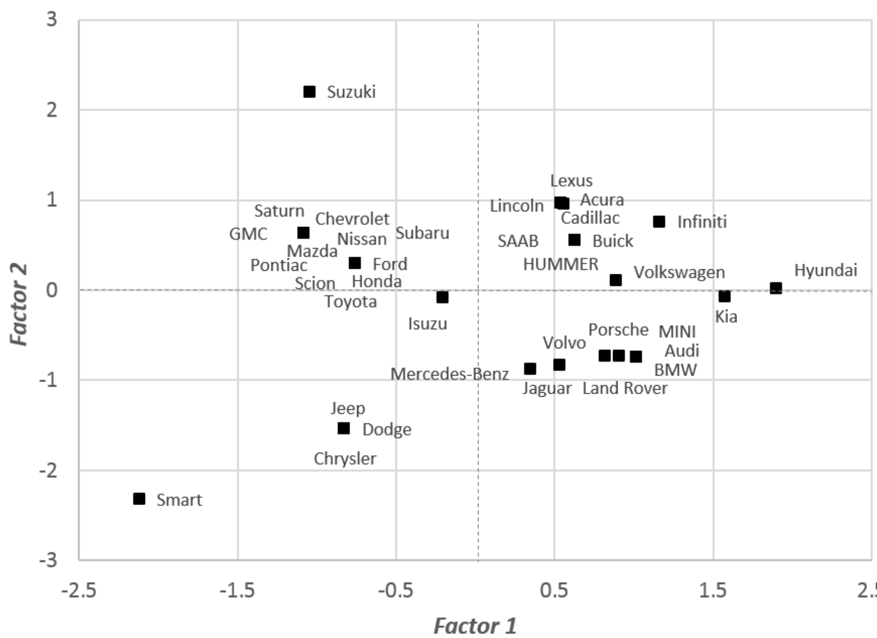

Figure 4.1: Resulting scores of automobile producers' 2008 warranty coverage

related warranties and power-train-specific warranties are significantly different, and that these decisions should be investigated separately. Therefore, we denote the resulting score of the first factor of producer i at year t as $WarrantyLength\_NonPower_{i,t}$ and use it as a proxy for the length of non-power-train-related warranties. We also denote the resulting score of the second factor as $WarrantyLength\_Power_{i,t}$ and use it as a proxy for the length of power-train-specific warranties.

Extent of Buy-backs: We identify transactions in the CES that indicate households trading in their used vehicles as buy-back activities and count the number of such transactions. Since expenditures pertaining to vehicles are only reported for a reference period that is three months before the moment when a household was interviewed, we multiply that number by 4 to estimate the number of annual trade-ins, and denote it as $UsedTradeIns_{i,t}$. In addition, we normalize the measure by the total vehicle ownership of the producer, $TotalStock_{i,t}$, to control for differences in market size. The measure shows a fraction of the stock being traded-in, and we use it as a proxy for *the extent of buy-backs*. Furthermore, to control for the extreme value issue, we take the natural log of the value. As a result, we calculate the measure as:

$$BuyBack_{i,t} = \ln\left(\frac{UsedTradeIns_{i,t}}{TotalStock_{i,t}}\right)$$

Trade Volume in the Secondary Market: Leveraging vehicle ownership information in the CES, we obtain the number of used-vehicle purchases, $UsedPurchases_{i,t}$, by counting the newly added ownership of used vehicles of producer i from the previous October to the September of year t. We then define the *trade volume in the secondary market* as:

$$UsedTradeVolume_{i,t} = \ln\left(\frac{UsedPurchases_{i,t}}{TotalStock_{i,t}}\right)$$

Similar to the approach defining *the extent of buy-backs*, we also normalize the measure by the total stock of a producer and take the natural log of the value.

Producer's Used-Vehicle Reliability: We construct our key independent variable using automobile producers' reliability scores from J. D. Power's VDS. For ease of interpretation, we take the negative of the sales-weighted PP100 and divide it by 100. The used-vehicle reliability of producer i at year t is

$$UsedReliability_{i,t} = -\frac{WeightedPP100_{i,t}}{100}.$$

As a result, $UsedReliability_{i,t}$ is always negative, and a higher $UsedReliability_{i,t}$ indicates a automobile producer with more reliable used vehicle. In addition, to strengthen the link between a producer's used-vehicle reliability and its warranty-length decision, we further categorize problems in the VDS by distinguishing them as non-power-train-related problems or power-train-specific problems, and obtain the producer's non-power-train reliability as $UsedReliability\_NonPower_{i,t}$, and power-train related reliability as $UsedReliability\_Power_{i,t}$. Table 4.2 reports descriptive statistics and correlations of our measures.

Table 4.2: Descriptive statistics and correlations

	Variables	Mean	S.D	Min	Max	1	2	3	4	5	6
1	Used-Vehicle Reliability	-1.686	0.450	-3.443	-0.707						
2	Non-Power-Train Reliability	-1.413	0.372	-2.772	-0.642	0.984***					
3	Power-Train Reliability	-0.273	0.107	-0.672	-0.065	0.781***	0.656***				
4	Non-Power-Train Warranty Length	0.000	0.960	-2.531	2.080	0.115	0.113	0.088			
5	Power-Train Warranty Length	0.000	0.876	-2.729	-2.206	0.033	-0.002	0.145**	0.006		
6	Extent of Buy-backs	-4.553	0.524	-6.265	-2.979	-0.202***	-0.163**	-0.287***	0.158**	-0.110	
7	Trade Volume in the Secondary Market	-2.835	0.474	-4.595	- 1.099	-0.046	-0.041	-0.052	0.043	-0.154**	0.099

Notes: *** $p<0.01$, ** $p<0.05$, * $p<0.10$

4.3.3 Empirical Approaches

We obtained data from 2008 to 2013 and constructed our measures for this time period. As a result, our dataset is an unbalanced panel dataset.[2] By employing a panel data model, we can observe automobile producers' used-vehicle reliability and their warranty-length decisions over time, and control for the impact of mis-measured or omitted variables across producers and time.

To examine the curvilinear relationship proposed in Hypothesis 1, we incorporate the quadratic term of the independent variable, and expect the coefficients of the linear term and the quadratic term to be positive and statistically significant. We test the hypothesis for both the length of non-power-train warranties and the length of power-train warranties with

[2]6 of 37 automobile producers miss some of their reliability scores because of insufficient survey samples or ceased operations during our observation window. All of our results hold if we conduct our tests on a balanced dataset by excluding these producers.

the corresponding reliability. Consequently, we use the following two empirical models:

$$WarrantyLength\_NonPower_{i,t} =$$
$$\beta_1\, UsedReliability\_NonPower_{i,t} + \beta_2\, UsedReliability\_NonPower_{i,t}{}^2 + \gamma_t + \varepsilon_{i,t},$$
$$WarrantyLength\_Power_{i,t} =$$
$$\beta_1\, UsedReliability\_Poweri,t + \beta_2\, UsedReliability\_Power_{i,t}{}^2 + \gamma_t + \varepsilon_{i,t}.$$

γ_t represents time fixed effects to account for macro-level temporal conditions. To choose a proper specification, we conduct a number of diagnostic tests. When the length of non-power-train warranties is the dependent variable, the Hausman test that assesses a random effect specification versus a fixed effect specification for the model does not reject the null hypothesis ($\chi^2 = 5.76$ with $p = 0.330$), suggesting estimators from a random effect specification are consistent. However, the result of the Breusch-Pagan test ($\chi^2 = 385.75$ with $p < 0.001$) indicates the existence of groupwise heteroscedasticity, and the result of the Wooldridge test raises a concern regarding autocorrelation ($F = 4.59$ with $p = 0.040$). Therefore, we deploy a GLS specification with panel-specific AR(1) to control for heteroscedasticity and autocorrelation. When the length of power-train warranties is the dependent variable, the results are similar except that the result of the Wooldridge test does not raise a concern regarding autocorrelation ($F = 2.74$ with $p = 0.107$). Therefore, we deploy a GLS specification and control for heteroscedasticity.

To examine our second and third hypotheses, we regress the extent of buy-backs and the trade volume in the secondary market on producers' used-vehicle reliability. When the extent of buy-backs is the dependent variable, the result of the Hausman test ($\chi^2(4) = 8.77$ with $p = 0.187$) suggests that a random effect specification is consistent and efficient. The result of the Wooldridge test further indicates no concern for autocorrelation ($F = 2.23$ with $p = 0.146$). Nevertheless, the result of the Breusch-Pagan test still indicates the existence of heteroscedasticity ($\chi^2 = 25.92$ with $p < 0.001$). Therefore, we also deploy a GLS specification and control for heteroscedasticity for the following model to test Hypothesis 2:

$$BuyBack_{i,t} = \beta_1\, UsedReliability_{i,t} + \gamma_t + \varepsilon_{i,t}.$$

When the trade volume in the secondary market is the dependent variable, the result of the Hausman test ($\chi^2(4) = 18.49$ with $p = 0.001$) indicates that to obtain consistent estimators, a fixed effect specification is needed. In addition, the result of the modified Wald test ($\chi^2 = 158.87$ with $p < 0.001$) and that of the Wooldridge test ($F = 5.771$ with $p = 0.022$) indicate the existence of groupwise heteroscedasticity and autocorrelation. Therefore, we incorporate producer fixed effects, α_i, and the lagged dependent variable, and use robust standard errors. Consequently, the model for Hypothesis 3 is:

$$\begin{aligned} &UsedTradeVolume_{i,t} = \\ &\qquad \beta_1\, UsedReliability_{i,t} + \alpha_i + \gamma_t + \lambda\, UsedTradeVolume_{i,t-1} + \varepsilon_{i,t}. \end{aligned}$$

4.4 Results

We present our main results in Table 4.3. The result of model 1 in Table 4.3 shows that the association between the length of non-power-train-related warranties and non-power-train reliability is convex ($\beta_1 = 1.175$ with $p = 0.000$ and $\beta_2 = 0.303$ with $p = 0.000$), which supports our Hypothesis 1. However, while the result of model 2 shows that the relationship between the length of power-train warranties and power-train reliability is also convex, the estimator of the quadratic term is statistically insignificant ($\beta_1 = 2.724$ with $p = 0.067$ and $\beta_2 = 2.256$ with $p = 0.250$). Therefore, we find partial support for our Hypothesis 1 and show that automobile producers are more likely to offer longer warranties, particularly on basic warranties, when their used-vehicle reliability is either high or low compared to that when their reliability is at market average.

From the result of model 3 in Table 4.3, we find that the association between the ex-

Table 4.3: Main results

Variables	Model 1 $WarrantyLength\_NonPower$	Model 2 $WarrantyLength\_Power$	Model 3 $BuyBack$	Model 4 $UsedTradeVolume$
$UsedReliability\_NonPower$	1.175***			
	(0.274)			
$UsedReliability\_NonPower^2$	0.303***			
	(0.081)			
$UsedReliability\_Power$		2.724*		
		(1.486)		
$UsedReliability\_Power^2$		2.256		
		(1.963)		
$UsedReliability$			-0.349***	0.784***
			(0.085)	(0.202)
Lagged $UsedTradeVolume$				-0.139*
				(0.073)
Observations	198	198	177	158
χ^2	49.02	31.35	25.96	
R^2				0.1911
Producer fixed effects	N	N	N	Y

Notes: Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.10

tent of buy-backs and used-vehicle reliability is negative and statistically significant (β_1 is -0.348 with $p < 0.001$), which supports our Hypothesis 2. From the result of model 4, we also find that the association between the trade volume of a producer's used vehicles in the secondary market and used-vehicle reliability is positive and statistically significant (β_1 is 0.783 with $p < 0.001$), which supports our Hypothesis 3.

4.5 Robustness Checks

We then examine the robustness of our main findings to: (i) alternative measures for producers' used-vehicle reliability and (ii) alternative measures and an alternative model for the secondary market trade volume. Tables of results for the robustness checks are included in the Appendix.

4.5.1 Producer's Used-Vehicle Reliability

As mentioned, the VDS calculates producers' reliability score by weighting the PP100 of vehicle models by their sales. To control for any potential influence from the sales-weighting mechanism, we obtain producers' un-weighted reliability scores, which simply averages reliability scores across vehicle models. We also obtain their un-weighted non-power-train reliability and un-weighted power-train reliability scores. The results corresponding to these alternative measures (reported in Table C.1 of Appendix) are similar to our main results. Additionally, we find support for Hypothesis 1 from the association between the length of power-train warranties and power-train reliability.

We also regress the length of non-power-train warranties and that of power-train warranties on producers' overall reliability scores. The results (reported in models 2-1 and 2-2, respectively, in Table C.2 of Appendix) still partially support our Hypothesis 1. That is, we find support for our Hypothesis 1 from the association between the length of non-power-train warranties and non-power-train reliability, but not from the association between the length of power-train warranties and power-train reliability. We further alternate the non-power-train reliability and the power-train reliability to examine the consistency of findings regarding Hypothesis 2 and 3. The results (models 2-3 to 2-6 in Table C.2 of Appendix) similarly support our findings.

4.5.2 Trade Volume in the Secondary Market

We construct an alternative measure for the volume of trade in the secondary market as specified in Rao *et al.* (2009):

$$VOT_{i,t} = \ln\left(\frac{UsedPurchases_{i,t} + UsedSales_{i,t} + UsedTradeIns_{i,t}}{TotalStock_{i,t}}\right).$$

$UsedSales_{i,t}$ is the number of transactions that indicate used vehicles are sold (not traded-in) in the CES. Since such transactions are also reported in a three-month reference period only, we multiply that number by 4 to approximate annual used-vehicle sales. The result of using this alternative dependent variable also supports our Hypothesis 3 (model 3-1 in Appendix Table C.3). In addition, we use another measure in which we exclude

$UsedTradeIns_{i,t}$, and the result is still consistent (model 3-2 in Appendix Table C.3). Furthermore, because the ordinary least square regression on a dynamic panel data model with fixed effects does not address potential biases caused by the lagged dependent variable, we deploy the Arellano-Bond model, a Generalized Method of Moments (GMM) specification, to control for possible biases. The result still supports our Hypothesis 3 (model 3-3 in Appendix Table C.3)

4.6 Discussion and Conclusion

We find evidence that the relationship between automobile producers' non-power-train reliability and the length of basic warranties is curvilinear (U-shaped), which supports our Hypothesis 1. However, we do not find support for such a relationship between producers' power-train reliability and the length of power-train warranties, i.e., the result suggests that the relationship is linear and negative. We propose two potential explanations for this finding: first, the repair or replacement cost of power-train components is known to be higher than that of non-power-train components. As mentioned in Corollary 3.4, when the warranty cost factor C_w is not sufficiently small, threshold $f''_{PP} > 1$, resulting in a threshold policy for the warranty-length decision. Producers are less likely to offer longer warranties when its used-product reliability is low, which is consistent with the finding. Second, our analysis examines a producer's decision at the product level. The model may not be sufficient to address a circumstance where a component has a disproportionate cost compared to its value. More specifically, while the value of power-train components may not be proportional to the cost of their repair or replacement, the producer's decision on whether to exercise a buy-back program still relies on unit-level prices and costs. This explanation certainly warrants an area for future exploration. Regarding automobile producers' buy-back activities and the trade volume of their used vehicles with respect to used-vehicle reliability, we find support for Hypothesis 2 and 3. More specifically, we show that an automobile producer with better use-vehicle reliability buys back fewer of its used vehicles and that the trade volume of its used vehicles is greater.

We recognize that our empirical findings may be subject to the data sources that we use for our measures. For example, because of VDS's methodology, our reliability measure is limited to vehicles that are in use for three years. While a broader and better measure that comprehensively captures the reliability of products over time is always highly desirable, the VDS is recognized as one of the most well-known sources regarding used vehicle reliability (NADA 2015). Meanwhile, while the CES is often used as a source for vehicle ownership and related transactions (Rao *et al.* 2009, Peterson & Schneider 2016), it mainly focuses on consumer expenditures and does not capture additional information, such as whether a used vehicle is purchased from or traded into a dealer of the same producer. Nevertheless, obtaining comprehensive transaction details across producers and between customers for widely-used durable goods such as automobiles is always challenging, and the CES is perhaps the most credible and representative data source (Rao *et al.* 2009). Lastly, while our analytical and empirical examinations focus on the US automobile market, our findings and insights may be applicable to other durable products with active secondary markets.

Notwithstanding the above, our empirical findings in the US automobile market support our analytical predictions, and they are robust to alternative measures of our key independent variable, used-vehicle reliability, and to alternative measures for secondary market trade volume. Most importantly, supported by both the analytical study (chapter 3) and the empirical work (chapter 4), we offer a compelling explanation to durable-goods producers' decisions on the length of product warranties with respect to product reliability. Offering longer warranties can be profitable when the reliability of used products and the engagement of secondary market interference are properly aligned. Producers should evaluate their warranty-length decisions jointly with their decisions on secondary market interference.

Appendices

APPENDIX A

TABLES OF RESULTS FOR ROBUSTNESS CHECKS IN CHAPTER 2

Table A.1: *PointsRatio* as an alternative measure of change in relative assessed hazard level

Variables	Model 1 ER	Model 2 SR	Model 3 ΔEOP	Model 4 ER	Model 5 SR	Model 6 ΔEOP
PointsRatio = Increase	3.63**	3.22*	-2.29	3.38**	3.16*	-2.21
	(0.04)	(0.05)	(0.45)	(0.06)	(0.06)	(0.46)
Leanness				14.71**	8.46*	-13.76*
				(0.00)	(0.08)	(0.07)
Leanness when PointsRatio = Increase				-12.01**	-2.63	6.49
				(0.03)	(0.58)	(0.47)
Market concentration	20.52**	14.47	8.75	20.80**	14.86	9.12
	(0.03)	(0.16)	(0.56)	(0.03)	(0.15)	(0.54)
Industry growth	-0.00	-0.01	0.05***	-0.00	-0.01	0.05***
	(0.88)	(0.56)	(0.00)	(0.86)	(0.54)	(0.00)
Operating scale change	-0.00	0.01	-0.02	-0.00	0.01	-0.02
	(0.79)	(0.46)	(0.40)	(0.80)	(0.45)	(0.37)
Facility size	-15.72***	-20.61***	11.94	-15.75***	-20.60***	11.98
	(0.00)	(0.00)	(0.19)	(0.00)	(0.00)	(0.19)
Facility size∧2	1.59***	2.45***	-1.33	1.59***	2.45***	-1.35
	(0.01)	(0.00)	(0.18)	(0.01)	(0.00)	(0.17)
Operational complexity	-1.54***	0.06	-0.29	-1.71***	-0.07	-0.17
	(0.00)	(0.81)	(0.25)	(0.00)	(0.80)	(0.51)
Lagged ER	-0.41***			-0.41***		
	(0.00)			(0.00)		
Lagged ER∧2	-0.00*			-0.00*		
	(0.06)			(0.06)		
Lagged SR		-0.45***			-0.45***	
		(0.00)			(0.00)	
Lagged SR∧2		-0.00**			-0.00**	
		(0.02)			(0.02)	
Lagged ΔEOP			-0.46***			-0.46***
			(0.00)			(0.00)
Lagged ΔEOP∧2			-0.00***			-0.00***
			(0.01)			(0.01)

Table A.1: $PointsRatio$ as an alternative measure of change in relative assessed hazard level (*continued*)

Variables	Model 1 ER	Model 2 SR	Model 3 ΔEOP	Model 4 ER	Model 5 SR	Model 6 ΔEOP
Observations	43,400	43,400	14,622	43,400	43,400	14,622
R-squared	0.2139	0.2288	0.2346	0.2144	0.2290	0.2349

Notes: Robust p-values in parentheses: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$; Fixed effect estimates are omitted for brevity. In model 4 (emissions reductions), the effect of leanness when *RelHazard* = *Increased* is $\beta_2 + \beta_3 = 2.70$ with $p = 0.623$. In model 5 (use of source reduction), the effect of leanness when *RelHazard* = *Increased* is $\beta_2 + \beta_3 = 5.83$ with $p = 0.272$. In model 6 (use of EOP treatment), the effect of leanness when *RelHazard* = *Increased* is $\beta_2 + \beta_3 = -7.27$ with $p = 0.445$.

Table A.2: $RankRatio$ as an alternative measure of change in relative assessed hazard level

Variables	Model 1 ER	Model 2 SR	Model 3 ΔEOP	Model 4 ER	Model 5 SR	Model 6 ΔEOP
RelHazard = No Change	-1.07	-0.21	-4.07	-0.77	-0.70	-4.02
	(0.73)	(0.94)	(0.43)	(0.81)	(0.82)	(0.43)
RelHazard = Increased	7.08**	4.79	1.14	7.31**	4.73	0.87
	(0.02)	(0.11)	(0.78)	(0.02)	(0.11)	(0.83)
RankRatio	-0.50	18.04	-7.64	-11.16	21.98	-0.72
when RelHazard = Increased	(0.31)	(0.22)	(0.45)	(0.37)	(0.18)	(0.41)
Leanness				6.14	15.31**	-22.19*
				(0.47)	(0.04)	(0.07)
Leanness				-3.81	-16.60*	19.75
when RelHazard = No Change				(0.70)	(0.08)	(0.25)
Leanness				4.46	-1.69	13.99
when RelHazard = Increased				(0.65)	(0.84)	(0.28)
Leanness × RankRatio				-157.18	86.39	-12.04
				(0.35)	(0.64)	(0.96)
Leanness × RankRatio				49.08	-153.91	37.91
when RelHazard = Increased				(0.79)	(0.43)	(0.89)
Market concentration	20.92**	14.90	8.20	22.02**	16.22	9.20
	(0.03)	(0.15)	(0.58)	(0.02)	(0.12)	(0.54)
Industry growth	-0.00	-0.01	0.05***	-0.00	-0.01	0.05***
	(0.88)	(0.56)	(0.00)	(0.84)	(0.51)	(0.00)
Operating scale change	-0.00	0.01	-0.02	-0.00	0.01	-0.02
	(0.79)	(0.46)	(0.39)	(0.82)	(0.44)	(0.33)
Facility size	-15.64***	-20.56***	11.99	-15.62***	-20.60***	11.70
	(0.00)	(0.00)	(0.19)	(0.00)	(0.00)	(0.20)
Facility size∧2	1.58***	2.44***	-1.34	1.58***	2.44***	-1.34
	(0.01)	(0.00)	(0.18)	(0.01)	(0.00)	(0.18)
Operational complexity	-1.52	0.07	-0.28	-1.69***	-0.04	-0.17
	(0.00)	(0.78)	(0.27)	(0.00)	(0.87)	(0.50)
Lagged ER	-0.41***			-0.41***		
	(0.00)			(0.00)		
Lagged ER∧2	-0.00*			-0.00*		
	(0.06)			(0.06)		
Lagged SR		-0.45***			-0.45***	
		(0.00)			(0.00)	
Lagged SR∧2		-0.00**			-0.00**	
		(0.02)			(0.02)	

Table A.2: $RankRatio$ as an alternative measure of change in relative assessed hazard level (*Continued*)

Variables	Model 1 ER	Model 2 SR	Model 3 ΔEOP	Model 4 ER	Model 5 SR	Model 6 ΔEOP
Lagged ΔEOP			-0.46***			-0.46***
			(0.00)			(0.00)
Lagged ΔEOP∧2			0.00***			0.00***
			(0.01)			(0.01)
Observations	43,400	43,400	14,622	43,400	43,400	14,622
R-squared	0.2141	0.2290	0.2350	0.2145	0.2293	0.2356

Notes: Robust p-values in parentheses: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$; The estimated coefficients for *RelHazard = No Change* are grayed out for readability; Fixed effect estimates are omitted for brevity. To interpret the effect of leanness, we set the *RankRatio* value for an increase in relative assessed hazard level to be one standard deviation above the mean (i.e., $\mu_{RankRatio}$ $+\sigma_{RankRatio}$) whereas we set the value for a decrease in relative assessed hazard level to be one standard deviation below the mean (i.e., $\mu_{RankRatio}$ $-\sigma_{RankRatio}$), where $\mu_{RankRatio} = 0.001$ and $\sigma_{RankRatio} = 0.046$. Let β_4 be the coefficient of $Leanness \times RankRatio$ when *RelHazard = Decreased* and β_5 be the coefficient of $Leanness \times RankRatio$ when *RelHazard = Increased*. In model 4, the effect of leanness when *RelHazard = Decreased* is $\beta_2 + \beta_4 \times (\mu_{RankRatio} - \sigma_{RankRatio}) = 13.55$ with $p = 0.016$ while the effect of leanness when *RelHazard = Increased* is $\beta_2 + \beta_3 + (\beta_4 + \beta_5) \times (\mu_{RankRatio} + \sigma_{RankRatio}) = -5.80$ with $p = 0.310$. In model 5, the effect of leanness when *RelHazard = decreased* is $\beta_2 + \beta_4 \times (\mu_{RankRatio} - \sigma_{RankRatio}) = 11.24$ with $p = 0.059$ while the effect of leanness when *RelHazard = Increased* is $\beta_2 + \beta_3 + (\beta_4 + \beta_5) \times (\mu_{RankRatio} + \sigma_{RankRatio}) = 10.62$ with $p = 0.049$. In model 6, the effect of leanness when *RelHazard = decreased* is $\beta_2 + \beta_4 \times (\mu_{RankRatio} - \sigma_{RankRatio}) = 21.63$ with $p = 0.035$ while the effect of leanness when *RelHazard = Increased* is $\beta_2 + \beta_3 + (\beta_4 + \beta_5) \times (\mu_{RankRatio} + \sigma_{RankRatio}) = 7.06$ with $p = 0.453$.

Table A.3: Using all chemicals in the SPL, and $PointsRatio$ as the measure of change in relative assessed hazard level

Variables	Model 1 ER	Model 2 SR	Model 3 ΔEOP	Model 4 ER	Model 5 SR	Model 6 ΔEOP
PointsRatio = Increase	2.89**	3.19*	0.84	2.75*	3.09**	-0.96
	(0.04)	(0.02)	(0.70)	(0.05)	(0.02)	(0.66)
Leanness				13.66***	9.33***	-15.93***
				(0.00)	(0.01)	(0.01)
Leanness when PointsRatio = Increase				-7.96**	-4.71	4.02
				(0.05)	(0.18)	(0.53)
Market concentration	22.67***	25.08***	0.91	23.01***	25.38***	1.07
	(0.00)	(0.00)	(0.94)	(0.00)	(0.00)	(0.93)
Industry growth	0.00	-0.00	0.04***	0.00	-0.00	0.04***
	(0.78)	(0.62)	(0.00)	(0.80)	(0.61)	(0.00)
Operating scale change	-0.00	0.01	0.00	0.00	0.01	0.00
	(1.00)	(0.50)	(0.88)	(0.94)	(0.47)	(0.96)
Facility size	-13.03***	-18.38***	15.45**	-13.03***	-18.38***	15.56**
	(0.00)	(0.00)	(0.03)	(0.00)	(0.00)	(0.03)
Facility size∧2	1.39***	2.30***	-1.77**	1.40***	2.30***	-1.80**
	(0.00)	(0.00)	(0.03)	(0.00)	(0.00)	(0.03)
Operational complexity	-1.42***	0.23	-0.56***	-1.59***	0.10	-0.41**
	(0.00)	(0.26)	(0.01)	(0.00)	(0.62)	(0.04)
Lagged ER	-0.42***			-0.42***		
	(0.00)			(0.00)		
Lagged ER∧2	-0.00*			-0.00*		
	(0.04)			(0.04)		
Lagged SR		-0.44***			-0.44***	
		(0.00)			(0.00)	
Lagged SR∧2		-0.00***			-0.00***	
		(0.00)			(0.00)	
Lagged ΔEOP			-0.44***			-0.44***
			(0.00)			(0.00)
Lagged ΔEOP∧2			0.00***			0.00***
			(0.00)			(0.00)
Observations	65,533	65,533	25,600	65,533	65,533	25,600
R-squared	0.2163	0.2273	0.2252	0.2167	0.2275	0.2257

Notes: Robust p-values in parentheses: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$; Fixed effect estimates are omitted for brevity. In model 4, the effect of leanness when *RelHazard = Increased* is $\beta_2 + \beta_3 = 6.40$ with $p = 0.199$. In model 5, the effect of leanness when *RelHazard = Increased* is $\beta_2 + \beta_3 = 4.62$ with $p = 0.251$. In model 6, the effect of leanness when *RelHazard = Increased* is $\beta_2 + \beta_3 = -11.37$ with $p = 0.104$.

Table A.4: Rank variance to mean ratio ($RankVartoMeanRatio$) as an additional explanatory variable

Variables	Model 1 ER	Model 2 SR	Model 3 ΔEOP	Model 4 ER	Model 5 SR	Model 6 ΔEOP
RelHazard = No Change	-1.60	0.12	-4.84	-1.08	-0.36	-6.88*
	(0.48)	(0.96)	(0.19)	(0.66)	(0.87)	(0.10)
RelHazard = Increased	4.98**	3.51*	-0.09	4.60**	4.03**	-3.86
	(0.01)	(0.06)	(0.98)	(0.03)	(0.04)	(0.27)
Leanness				11.79**	11.83**	-21.52**
				(0.03)	(0.02)	(0.02)
Leanness when RelHazard = No Change				-1.91	-12.95*	19.26
				(0.47)	(0.94)	(0.17)
Leanness when RelHazard = Increased				-4.45	-0.38	13.46
				(0.47)	(0.94)	(0.17)
RankVartoMeanRatio	0.45	0.32	0.71	0.52	0.34	0.65
	(0.24)	(0.47)	(0.36)	(0.22)	(0.51)	(0.42)
RankVartoMeanRatio when RelHazard = No Change				-0.51	0.15	1.48
				(0.52)	(0.85)	(0.35)
RankVartoMeanRatio when RelHazard = Increased				0.09	0.11	1.20**
				(0.76)	(0.84)	(0.00)
Market concentration	20.92**	14.99	8.40	21.83**	16.18	8.97
	(0.03)	(0.15)	(0.58)	(0.02)	(0.12)	(0.55)
Industry growth	-0.00	-0.01	0.05***	-0.00	-0.01	0.05***
	(0.85)	(0.54)	(0.00)	(0.81)	(0.51)	(0.00)
Operating scale change	-0.00	0.01	-0.02	-0.00	0.01	-0.02
	(0.81)	(0.45)	(0.40)	(0.84)	(0.44)	(0.36)
Facility size	-15.66***	-20.59***	11.85	-15.66***	-20.62***	11.96
	(0.00)	(0.00)	(0.19)	(0.00)	(0.00)	(0.19)
Facility size∧2	1.58***	2.45***	-1.32	1.58***	2.45***	-1.34
	(0.01)	(0.00)	(0.18)	(0.01)	(0.00)	(0.18)
Operational complexity	-1.54***	0.06	-0.29	-1.70***	-0.05	-0.19
	(0.00)	(0.82)	(0.26)	(0.00)	(0.83)	(0.45)
Lagged ER	-0.41***			-0.41***		
	(0.00)			(0.00)		
Lagged ER∧2	-0.00*			-0.00*		
	(0.06)			(0.06)		
Lagged SR		-0.45***			-0.45***	
		(0.00)			(0.00)	
Lagged SR∧2		-0.00**			-0.00**	
		(0.02)			(0.02)	

Table A.4: Rank variance to mean ratio ($RankVartoMeanRatio$) as an additional explanatory variable (*continued*)

Variables	Model 1 ER	Model 2 SR	Model 3 ΔEOP	Model 4 ER	Model 5 SR	Model 6 ΔEOP
Lagged ΔEOP			-0.46***			-0.46***
			(0.00)			(0.00)
Lagged ΔEOP$\wedge$2			0.00***			0.00***
			(0.01)			(0.01)
Observations	43,400	43,400	14,622	43,400	43,400	14,622
R-squared	0.2140	0.2289	0.2348	0.2143	0.2292	0.2364

Notes: Robust p-values in parentheses: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$; The estimated coefficients for *RelHazard = No Change* are grayed out for readability; Fixed effect estimates are omitted for brevity. In model 4, the effect of leanness when *RelHazard = Increased* is $\beta_2 + \beta_3 = 6.24$ with $p = 0.194$. In model 5, the effect of leanness when *RelHazard = Increased* is $\beta_2 + \beta_3 = 11.45$ with $p = 0.029$. In model 6, the effect of leanness when *RelHazard = Increased* is $\beta_2 + \beta_3 = -8.06$ with $p = 0.380$. In model 6, the effect of rank variance on the use of EOP treatment when *RelHazard = Increased* is 1.84 with $p = 0.040$.

Table A.5: Local Environmental Preference (*LCVH*) as an additional explanatory variable

Variables	Model 1 ER	Model 2 SR	Model 3 ΔEOP	Model 4 ER	Model 5 SR	Model 6 ΔEOP
RelHazard = No Change	-1.72	0.48	-4.26	-1.86	0.16	-3.98
	(0.45)	(0.82)	(0.25)	(0.41)	(0.94)	(0.27)
RelHazard = Increased	5.00**	3.36*	-1.58	4.77**	3.38*	-1.47
	(0.01)	(0.07)	(0.62)	(0.02)	(0.06)	(0.64)
Leanness				10.59*	11.52**	-20.04**
				(0.05)	(0.03)	(0.03)
Leanness when RelHazard = No Change				-1.91	-14.48**	18.00
				(0.83)	(0.05)	(0.23)
Leanness when RelHazard = Increased				-3.78	-1.06	-12.89
				(0.55)	(0.84)	(0.18)
LCVH	-0.01	0.30**	-0.10	0.04	0.27**	-0.08
	(0.94)	(0.01)	(0.60)	(0.79)	(0.03)	(0.71)
LCVH when RelHazard = No Change				-0.50	0.03	-0.07
				(0.63)	(0.76)	(0.68)
LCVH when RelHazard = Increased				-0.09	0.05	0.00
				(0.30)	(0.55)	(1.00)
Market concentration	20.93**	15.00	8.14	21.69**	16.19	9.02
	(0.03)	(0.15)	(0.59)	(0.02)	(0.12)	(0.55)
Industry growth	0.00	-0.01	0.05***	-0.00	-0.01	0.05***
	(0.99)	(0.71)	(0.00)	(0.98)	(0.66)	(0.00)
Operating scale change	-0.00	0.01	-0.02	-0.00	0.01	-0.02
	(0.89)	(0.34)	(0.42)	(0.90)	(0.33)	(0.37)
Facility size	-16.10***	-19.95***	12.47	-16.15***	-19.96***	12.20
	(0.00)	(0.00)	(0.17)	(0.00)	(0.00)	(0.18)
Facility size∧2	1.69***	2.36***	-1.42	1.70***	2.36***	-1.41
	(0.00)	(0.00)	(0.15)	(0.00)	(0.00)	(0.15)
Operational complexity	-1.50***	-0.02	-0.31	-1.65***	-0.11	-0.22
	(0.00)	(0.95)	(0.22)	(0.00)	(0.67)	(0.40)
Lagged ER	-0.41***			-0.41***		
	(0.00)			(0.00)		
Lagged ER∧2	-0.00*			-0.00*		
	(0.06)			(0.06)		
Lagged SR		-0.45***			-0.45***	
		(0.00)			(0.00)	
Lagged SR∧2		-0.00**			-0.00**	
		(0.02)			(0.02)	

Table A.5: Local Environmental Preference (*LCVH*) as an additional explanatory variable (*continued*)

Variables	Model 1 ER	Model 2 SR	Model 3 ΔEOP	Model 4 ER	Model 5 SR	Model 6 ΔEOP
Lagged ΔEOP			-0.46***			-0.46***
			(0.00)			(0.00)
Lagged ΔEOP∧2			0.00***			0.00***
			(0.01)			(0.01)
Observations	43,167	43,167	14,550	43,167	43,167	14,550
R-squared	0.2153	0.2296	0.2342	0.2155	0.2299	0.2347

Notes: Robust p-values in parentheses: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$; The estimated coefficients for *RelHazard = No Change* are grayed out for readability; Fixed effect estimates are omitted for brevity. In model 4, the effect of leanness when *RelHazard = Increased* is $\beta_2 + \beta_3 = 6.81$ with $p = 0.222$. In model 5, the effect of leanness when *RelHazard = Increased* is $\beta_2 + \beta_3 = 10.46$ with $p = 0.047$. In model 6, the effect of leanness when *RelHazard = Increased* is $\beta_2 + \beta_3 = -7.15$ with $p = 0.438$.

Table A.6: Industry regulation (*GED_VA_Ratio*) as an additional explanatory variable

Variables	Model 1 ER	Model 2 SR	Model 3 ΔEOP	Model 4 ER	Model 5 SR	Model 6 ΔEOP
RelHazard = No Change	-1.25	0.24	-4.63	-1.39	-0.39	-4.87
	(0.58)	(0.91)	(0.21)	(0.55)	(0.86)	(0.18)
RelHazard = Increased	4.87**	3.42*	-1.09	4.44**	3.12*	-1.30
	(0.02)	(0.06)	(0.73)	(0.03)	(0.09)	(0.68)
Leanness				11.86**	11.89**	-21.72**
				(0.03)	(0.02)	(0.02)
Leanness when RelHazard = No Change				-2.12	-13.08*	18.82
				(0.77)	(0.07)	(0.21)
Leanness when RelHazard = Increased				-4.33	-0.43	14.18
				(0.49)	(0.94)	(0.15)
GED_VA_Ratio	1.61***	-0.47	0.57	1.77***	-0.18	0.17
	(0.00)	(0.21)	(0.31)	(0.00)	(0.66)	(0.79)
GED_VA_Ratio when RelHazard = No Change				-0.08	-0.51*	0.69
				(0.81)	(0.08)	(0.15)
GED_VA_Ratio when RelHazard = Increased				-0.48**	-0.30*	0.38
				(0.02)	(0.09)	(0.14)
Market concentration	22.81**	14.39	8.85	23.77**	15.44	9.69
	(0.02)	(0.16)	(0.55)	(0.01)	(0.14)	(0.52)
Industry growth	0.01	-0.01	0.06***	0.01	-0.01	0.06***
	(0.46)	(0.41)	(0.00)	(0.51)	(0.36)	(0.00)
Operating scale change	-0.00	0.01	-0.02	-0.00	0.01	-0.02
	(0.76)	(0.44)	(0.40)	(0.77)	(0.42)	(0.32)
Facility size	-15.99***	-20.55***	11.57	-16.12***	-20.70***	11.68
	(0.00)	(0.00)	(0.20)	(0.00)	(0.00)	(0.20)
Facility size∧2	1.62***	2.45***	-1.29	1.62***	2.46***	-1.32
	(0.00)	(0.00)	(0.19)	(0.00)	(0.00)	(0.18)
Operational complexity	-1.53***	0.06	-0.29	-1.68***	-0.06	-0.17
	(0.00)	(0.82)	(0.26)	(0.00)	(0.82)	(0.51)
Lagged ER	-0.41***			-0.41***		
	(0.00)			(0.00)		
Lagged ER∧2	-0.00*			-0.00*		
	(0.06)			(0.06)		
Lagged SR		-0.45***			-0.45***	
		(0.00)			(0.00)	
Lagged SR∧2		-0.00**			-0.00**	
		(0.02)			(0.02)	

Table A.6: Industry regulation (*GED_VA_Ratio*) as an additional explanatory variable (*continued*)

Variables	Model 1 ER	Model 2 SR	Model 3 ΔEOP	Model 4 ER	Model 5 SR	Model 6 ΔEOP
Lagged ΔEOP			-0.46***			-0.46***
			(0.00)			(0.00)
Lagged ΔEOP∧2			0.00***			0.00***
			(0.01)			(0.01)
Observations	43,398	43,398	14,622	43,398	43,398	14,622
R-squared	0.2145	0.2289	0.2348	0.2149	0.2293	0.2359

Notes: Robust p-values in parentheses: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$; The estimated coefficients for *RelHazard = No Change* are grayed out for readability; Fixed effect estimates are omitted for brevity. In model 4, the effect of leanness when *RelHazard = Increased* is $\beta_2 + \beta_3 = 7.53$ with $p = 0.176$. In model 5, the effect of leanness when *RelHazard = Increased* is $\beta_2 + \beta_3 = 11.46$ with $p = 0.029$. In model 6, the effect of leanness when *RelHazard = Increased* is $\beta_2 + \beta_3 = -7.54$ with $p = 0.412$.

APPENDIX B

PROOFS OF CHAPTER 3

B.1 Benchmark Model

We first solve the producer's problem if it offers short warranties and assume $\rho \to 1$. Since strategy $N^S N^S$ is active if $\theta_1^S < 1$, we identify the solutions in the following conditions:

Case S1 ($\theta_1^S \leq 1$): The condition implies $P_n^S \leq 1-(1-f_u)\delta$. Since all three customer strategies, $N^S N^S$, $N^S K^S$, and II,are active, $Q_n^S(P_n^S) = 1 - \frac{P_n^S}{1-(1-f_u)^2\delta^2}$ and $Q_k^S(P_n^S) = \frac{(1-f_u)\delta P_n^S}{1-(1-f_u)^2\delta^2}$. The producer's problem is concave in the decision variable P_n^S (i.e., $\frac{\partial^2 \Pi^S}{\partial P_n^{S2}} = -\frac{2}{1-(1-f_u)^2\delta^2}$ and is negative when $0 \leq \delta \leq 1$ and $0 \leq f_u \leq 1$). The KKT Lagrangian equation is $\mathcal{L} = \Pi^S + \lambda_1(1-(1-f_u)\delta - P_n^S)$ and the KKT conditions are: (1)$\frac{\partial \mathcal{L}}{\partial P_n^S} = 0$, (2)$\lambda_1(\frac{\partial \mathcal{L}}{\partial \lambda_1}) = 0 \Rightarrow \lambda_1(1-(1-f_u)\delta - P_n^S) = 0$,(3)$\lambda_1 \geq 0$, and (4)$1-(1-f_u)\delta - P_n^S \geq 0$. We also incorporate following conditions for the feasibility of the solution: (i) $1 > f_u > 0$, (ii) $1 > \delta > 0$, and (iii) $\mathbb{C} \geq 0$. The analysis identifies two candidate solutions: **Solution 1 ($P_n^S = 1-(1-f_u)\delta$):** We solve $\lambda_1 \geq 0$ and $\frac{\partial \mathcal{L}}{\partial P_n^S} = 0$ simultaneously and get $\lambda_1 = \frac{\mathbb{C}-(1-(1-f_u)\delta)^2}{1-(1-f_u)^2\delta^2}$ and a condition $(1-(1-f_u)\delta)^2 \leq \mathbb{C} \leq 1-(1-f_u)\delta$. In addition, we have $Q_n^{S*} = \frac{(1-f_u)\delta}{1+(1-f_u)\delta} = Q_k^{S*}$, and $\Pi^{S*} = \frac{(1-f_u)\delta(1-\mathbb{C}-(1-f_u)\delta)}{1+(1-f_u)\delta}$. **Solution 2 ($P_n^S < 1-(1-f_u)\delta$):** We solve $\lambda_1 = 0$ and $\frac{\partial \mathcal{L}}{\partial P_n^S} \geq 0$ simultaneously and get a condition $\mathbb{C} < (1-(1-f_u)\delta)^2$. We have $P_n^{S*} = \frac{\left(1+\mathbb{C}-(1-f_u)^2\delta^2\right)}{2}$ In addition, $Q_n^{S*} = \frac{1-\mathbb{C}-(1-f_u)^2\delta^2}{2(1-(1-f_u)\delta)(1+(1-f_u)\delta)}$, $Q_k^{S*} = \frac{(1-f_u)\delta(1+\mathbb{C}-(1-f_u)^2)}{2(1-(1-f_u)\delta)(1+(1-f_u)\delta)}$, and $\Pi^{S*} = \frac{(1-\mathbb{C}-(1-f_u)^2\delta^2)^2}{4(1-(1-f_u)^2\delta^2)}$.

Case S2 ($\theta_1^S \geq 1$): The condition implies $P_n^S \geq 1-(1-f_u)\delta$. Since only customer strategies $N^S K^S$ and II are active, $Q_n^S(P_n^S) = Q_k^S(P_n^S) = \frac{1}{2}\left(1 - \frac{P_n^S}{1+(1-f)\delta}\right)$. The producer's problem is also concave in P_n^S (i.e., $\frac{\partial^2 \Pi^S}{\partial P_n^{S2}} = -\frac{1}{1+(1-f_u)\delta}$ and is negative when $0 \leq \delta \leq 1$ and $0 \leq f_u \leq 1$). The KKT Lagrangian equation is $\mathcal{L} = \Pi^S + \lambda_1(P_n^S - (1-(1-f_u)\delta))$ and the KKT conditions are: (1)$\frac{\partial \mathcal{L}}{\partial P_n^S} = 0$, (2)$\lambda_1(\frac{\partial \mathcal{L}}{\partial \lambda_1}) = 0 \Rightarrow \lambda_1(P_n^S - (1-(1-f_u)\delta)) =$

0,(3)$\lambda_1 \geq 0$, and (4)$P_n^S - (1-(1-f_u)\delta) \geq 0$. We also incorporate following conditions for the feasibility of the solution: (i) $1 > f_u > 0$, (ii) $1 > \delta > 0$, and (iii) $\mathbb{C} \geq 0$. The analysis identifies two candidate solutions: **Solution 1 ($P_n^S = 1-(1-f_u)\delta$):** We solve $\lambda_1 \geq 0$ and $\frac{\partial \mathcal{L}}{\partial P_n^S} = 0$ simultaneously and get $\lambda_1 = \frac{1-3(1-f_u)\delta-\mathbb{C}}{2(1+(1-f_u)\delta)}$ and a condition $\mathbb{C} \leq 1-3(1-f_u)\delta$. In addition, we have $Q_n^{S*} = \frac{(1-f_u)\delta}{1+(1-f_u)\delta} = Q_k^{S*}$, and $\Pi^{S*} = \frac{(1-f_u)\delta(1-\mathbb{C}-(1-f_u)\delta)}{1+(1-f_u)\delta}$. **Solution 2 ($P_n^S > 1-(1-f_u)\delta$):** We solve $\lambda_1 = 0$ and $\frac{\partial \mathcal{L}}{\partial P_n^S} \geq 0$ simultaneously and get a condition $1-3(1-f_u)\delta < \mathbb{C} < 1+(1-f_u)\delta$. We has $P_n^{S*} = \frac{(1+\mathbb{C}+(1-f_u)\delta)}{2}$ under. In addition, $Q_n^{S*} = Q_k^{S*} = \frac{1-\mathbb{C}+(1-f_u)\delta}{4(1+(1-f_u)\delta)}$ and $\Pi^{S*} = \frac{(1-\mathbb{C}+(1-f_u)\delta)^2}{8(1+(1-f_u)\delta)}$.

We compare the optimal profits and find that the optimal profit of S1 is greater than that of case S2 when $\mathbb{C} < 1-\delta(1-f_u)\left(1+\sqrt{2-2\delta(1-f_u)}\right)$ or $\mathbb{C} > 1-\delta(1-f_u)\left(1-\sqrt{2-2\delta(1-f_u)}\right)$. We also find that $(1-(1-f_u)\delta)^2 < 1-\delta(1-f_u)\left(1-\sqrt{2-2\delta(1-f_u)}\right)$ and that $1-3(1-f_u)\delta < 1-\delta(1-f_u)\left(1+\sqrt{2+2\delta(1-f_u)}\right) < (1-(1-f_u)\delta)^2 < 1+(1-f_u)\delta$. As such, we denote $1+\delta(1-f_u)$ as $\widehat{\mathbb{C}_b^S}$ and $1-\delta(1-f_u)\left(1+\sqrt{2-2\delta(1-f_u)}\right)$ as $\widetilde{\mathbb{C}_b^S}$

We then solve the producer's problem if it offers long warranties. There are also two cases:

Case L1 ($\theta_1^L \leq 1$): The condition implies $P_n^L \leq 1-\delta$. Since all three customer strategies are active, $Q_n^L(P_n^L) = 1-\frac{P_n^L}{1-\delta^2}$ and $Q_k^L(P_n^L) = \frac{\delta P_n^L}{1-\delta^2}$. The producer's problem is concave in P_n^L (i.e., $\frac{\partial^2 \Pi^L}{\partial {P_n^L}^2} = -\frac{2}{1-\delta^2}$ and is negative when $0 \leq \delta \leq 1$). The KKT Lagrangian equation is $\mathcal{L} = \Pi^L + \lambda_1(P_n^L - (1-\delta))$ and the KKT conditions are: (1)$\frac{\partial \mathcal{L}}{\partial P_n^L} = 0$, (2)$\lambda_1(\frac{\partial \mathcal{L}}{\partial \lambda_1}) = 0 \Rightarrow \lambda_1(P_n^L - (1-\delta)) = 0$,(3)$\lambda_1 \geq 0$, and (4)$P_n^L - (1-\delta) \geq 0$. We also incorporate following conditions for the feasibility of the solution: (i) $1 > f_u > 0$, (ii) $1 > \delta > 0$, (iii) $\mathbb{C} \geq 0$, and (iv) $C_w \geq 0$. The analysis also identifies two candidate solutions: **Solution 1 ($P_n^L = 1-\delta$):** We solve $\lambda_1 \geq 0$ and $\frac{\partial \mathcal{L}}{\partial P_n^L} = 0$ simultaneously and get $\lambda_1 = \frac{\mathbb{C}-(1-\delta)^2-f_u\delta C_w}{1-\delta^2}$ and condition $(1-\delta)^2 + f_u\delta C_w < \mathbb{C} < 1-\delta-f_uC_w$ when $(1+\delta)f_uC_w + \delta^2 \leq \delta$. In addition, we have $Q_n^{S*} = \frac{\delta}{1+\delta} = Q_k^{S*}$, and $\Pi^{S*} = \frac{\delta(1-\mathbb{C}-\delta-f_uC_w)}{1+\delta}$. **Solution 2 ($P_n^L < 1-\delta$):** We solve $\lambda_1 = 0$ and $\frac{\partial \mathcal{L}}{\partial P_n^L} \geq 0$ simultaneously and get conditions: (i) $\mathbb{C} < (1-\delta)^2 + f_u\delta C_w$

when $(1+\delta)f_uC_w + \delta^2 \leq \delta$ and (ii) $\mathbb{C} < 1 + \delta f_uC_w - \delta^2 - 2\sqrt{\delta(1-\delta^2)f_uC_w}$ when $(1+\delta)f_uC_w + \delta^2 > \delta$. We have $P_n^{L*} = \frac{(1+\mathbb{C}-\delta^2-f_u\delta C_w)}{2}$. In addition, $Q_n^{L*} = \frac{1-\mathbb{C}-\delta^2+f_u\delta C_w}{2(1-\delta^2)}$, $Q_k^{L*} = \frac{\delta(1+\mathbb{C}-\delta^2-f_u\delta C_w}{2(1-\delta^2)}$, and $\Pi^{L*} = \frac{(1-\mathbb{C}-\delta^2)^2-2f_u\delta(1+\mathbb{C}-\delta^2)C_w+f_u^2\delta^2C_w^2}{4(1-\delta^2)}$.

Case L2 ($\theta_1^L \geq 1$): The condition implies $P_n^L \geq 1-\delta$. Since only customer strategies N^LK^L and II are active, $Q_n^L(P_n^L) = Q_k^L(P_n^L) = \frac{1}{2}\left(1 - \frac{P_n^L}{1+\delta}\right)$. The producer's problem is still concave in P_n^L (i.e., $\frac{\partial^2\Pi^L}{\partial P_n^{L2}} = -\frac{1}{1+\delta}$ and is negative when $0 \leq \delta \leq 1$). The KKT Lagrangian equation is $\mathcal{L} = \Pi^L + \lambda_1(P_n^L - (1-\delta))$ and the KKT conditions are: (1)$\frac{\partial\mathcal{L}}{\partial P_n^L} = 0$, (2)$\lambda_1(\frac{\partial\mathcal{L}}{\partial\lambda_1}) = 0 \Rightarrow \lambda_1(P_n^L - (1-\delta)) = 0$,(3)$\lambda_1 \geq 0$, and (4)$P_n^L - (1-\delta) \geq 0$. We also incorporate following conditions for the feasibility of the solution: (i) $1 > f_u > 0$, (ii) $1 > \delta > 0$, (iii) $\mathbb{C} \geq 0$, and (iv) $C_w \geq 0$. The analysis identifies two candidate solutions: **Solution 1 ($P_n^L = 1-\delta$):** We solve $\lambda_1 \geq 0$ and $\frac{\partial\mathcal{L}}{\partial P_n^L} = 0$ simultaneously and get $\lambda_1 = \frac{1-3\delta-\mathbb{C}-f_uC_w}{2(1+\delta)}$ and a condition $\mathbb{C} \leq 1-3\delta-f_uC_w$. In addition, we have $Q_n^{S*} = \frac{\delta}{1+\delta} = Q_k^{S*}$, and $\Pi^{S*} = \frac{\delta(1-\mathbb{C}-\delta-f_uC_w)}{1+\delta}$. **Solution 2 ($P_n^L > 1-\delta$):** We solve $\lambda_1 = 0$ and $\frac{\partial\mathcal{L}}{\partial P_n^L} \geq 0$ simultaneously and get a conditions that $1-3\delta-f_uC_w < \mathbb{C} < 1+\delta-f_uC_w$. We have $P_n^{L*} = \frac{(1+\mathbb{C}+\delta+f_uC_w)}{2}$. In addition, $Q_n^{L*} = Q_k^{L*} = \frac{1-\mathbb{C}+\delta-f_uC_w}{4(1+\delta)}$ and $\Pi^{L*} = \frac{(1-\mathbb{C}+\delta-f_uC_w)^2}{8(1+\delta)}$.

We find that the optimal profit of case L1 is greater than that of case L2 when $\mathbb{C} < 1-\delta+f_uC_w - \sqrt{2-2\delta}\,(f_uC_w+\delta)$ or $\mathbb{C} > 1-\delta+f_uC_w+\sqrt{2-2\delta}\,(f_uC_w+\delta)$. We also find that $1-\delta+f_uC_w+\sqrt{2-2\delta}\,(f_uC_w+\delta) > (1-\delta)^2+\delta f_uC_w$ and $1-\delta+f_uC_w+\sqrt{2-2\delta}\,(f_uC_w+\delta) > 1+\delta f_uC_w-\delta^2-2\sqrt{\delta(1-\delta^2)f_uC_w}$ and that $1+3\delta-f_uC_w < 1-\delta+f_uC_w-\sqrt{2-2\delta}\,(f_uC_w+\delta) < (1-\delta)^2+\delta f_uC_w < 1+\delta-f_uC_w$. As such, we denote $1+\delta-f_uC_w$ as $\widehat{\mathbb{C}_b^S}$ and $1-\delta+f_uC_w-\sqrt{2-2\delta}\,(f_uC_w+\delta)$ as $\widetilde{\mathbb{C}_b^L}$. Summarizing above optimal solutions, we have Proposition 3.1.

We next compare the optimal profits when the producer offers short warranties and that when the producer offers long warranties and refer to Δ_B as the difference, i.e., $\Delta = \Pi^{L*} - \Pi^{S*}$. If $\Delta_B > 0$, the producer should offer long warranties for greater profits. We first examine the scenario in which the strategy that customers discard used products is active regardless of the producer's warranty length decision. The scenario implies the condition

$\mathbb{C} < \min(\widetilde{\mathbb{C}_b^S}, \widetilde{\mathbb{C}_b^L})$ and has $\Delta_B = \frac{(1-\mathbb{C}-\delta^2)^2 - f_u\delta(1+\mathbb{C}-\delta^2)C_w + f_u^2\delta^2 C_w^2}{4(1-\delta^2)} - \frac{(1-\mathbb{C}-(1-f_u)^2\delta^2)^2}{4(1-(1-f_u)^2\delta^2)}$. Let $C_w = 0$, we find that $\Delta_B(f_u|C_w = 0) = 0$ has 4 roots (i.e., $f_u = 0$, $f_u = 2$, and $f_u = 1 \pm \frac{\sqrt{(1-\delta^2)(1-\mathbb{C}^2-\delta^2)}}{\delta(1-\delta^2)}$. We also find that both the irrational roots are $\notin [0,1]$ and that $\frac{\partial \Delta_B(f_u|C_w=0)}{\partial f_u}$ when $f \to 0$ is negative (i.e., $\frac{\partial \Delta_B(f_u|C_w=0)}{\partial f_u}(f_u \to 0) = \frac{\delta^2\left((1-\delta^2)^2 - \mathbb{C}^2\right)}{2(1-\delta^2)^2}$ and is negative when $\mathbb{C} < \widetilde{\mathbb{C}_b^L}$), which indicates that $\Delta_B < 0$ when $f_u \in [0,1]$ and $C_w = 0$. We then observe that Δ_B decreases in C_w (i.e., $\frac{\partial \Delta_B}{\partial C_w} = \frac{\delta f_u\left(\delta f_u C_w - \mathbb{C} + \delta^2 - 1\right)}{2(1-\delta^2)}$ and is negative when $0 \le \delta \le 1$ and $0 \le f_u \le 1$), which implies that $\Delta_B < 0$ always.

We then examine the scenario in which the strategy that customers discard used products is inactive regardless of the producer's warranty-length decision. We have $\mathbb{C} > \max(\widetilde{\mathbb{C}_b^S}, \widetilde{\mathbb{C}_b^L})$ and $\Delta_B = \frac{(1-\mathbb{C}+\delta-f_u C_w)^2}{8(1+\delta)} - \frac{(1-\mathbb{C}+(1-f_u)\delta)^2}{8(1-(1-f_u)\delta)}$. $\Delta_B(f_u) = 0$ always has 3 real roots (i.e., $f_u = 0$ and $f_u = \frac{-\delta^2-\delta^3+2\delta C_w+C_w^2-2\mathbb{C}\delta C_w+2\delta^2 C_w+\delta C_w^2 \pm \sqrt{1+\delta}(\delta-C_w)\sqrt{\delta^2(1+\delta)-2\delta C_w(1+\delta-2\mathbb{C})+(1+\delta)C_w^2}}{2\delta C_w^2}$). We exclude one of the non-zero root because it conflicts with $\mathbb{C} < \min(\widehat{\mathbb{C}_b^S}, \widehat{\mathbb{C}_b^L})$. The other non-zero root, denoted as f_B', is positive when $\frac{\delta(1+\delta+\mathbb{C})}{2(1+\delta)} < C_w < \delta$. f_B', is negative when $0 < C_w < \frac{\delta(1+\delta+\mathbb{C})}{2(1+\delta)}$. In addition, $\frac{\partial \Delta_B(f_u)}{\partial f_u}(f_u \to 0) = \frac{(1+\delta-\mathbb{C})(\delta(1+\delta+\mathbb{C})-2(1+\delta)C_w)}{8(1+\delta)^2} < 0$ when $\mathbb{C} < \frac{1+\delta}{\delta}(2C_w - \delta)$.

Therefore, if $\frac{\delta(1+\delta+\mathbb{C})}{2(1+\delta)} < C_w < \delta$, $f_B' > 0$, $\Delta_B(f_u) < 0$ when $f_u < f_B'$, and $\Delta_B(f_u) > 0$ when $f_u > f_B'$. If $0 < C_w < \frac{\delta(1+\delta+\mathbb{C})}{2(1+\delta)}$, $\Delta_B(f_u) > 0$ always. We then summarize above findings in Corollary 3.1.

B.2 Proof of Proposition 3.2

We assume $\rho \to 1$. To check the joint concavity of the producer's problem if it offers short warranties, we have the Hessian matrix as $\begin{pmatrix} -\frac{2}{1+3(1-f_u)\delta} & 0 \\ 0 & -\frac{2(1-f_u)\delta(1-(1-f_u)\delta)}{1+3(1-f_u)\delta} \end{pmatrix}$. The first principle minor of the matrix is $-\frac{2}{1+3(1-f_u)\delta}$ and is negative when $1 \ge \delta \ge 0$ and $1 \ge f_u \ge 0$. The second principle minor is $\frac{4(1-f_u)\delta(1-(1-f_u)\delta)}{(1+3(1-f_u)\delta)^2}$ and is positive under the same conditions. Therefore, the matrix is negative definite and indicates that the problem is concave with respect to the producer's decision variables. The KKT Lagrangian equation is $\mathcal{L} = \Pi^S + \lambda_1(Q_n^S(P_n^S, Q_u^S) - Q_u^S) + \lambda_2 Q_u^S$. The KKT conditions are: (1)$\frac{\partial \mathcal{L}}{\partial P_n^S} = 0$, (2)$\frac{\partial\mathcal{L}}{\partial Q_u^S}=0$, (3)$\lambda_1(\frac{\partial\mathcal{L}}{\partial\lambda_1})=0 \Rightarrow \lambda_1(Q_n^S(P_n^S,Q_u^S)-Q_u^S)=0$, (4)$\lambda_2(\frac{\partial\mathcal{L}}{\partial\lambda_2})=0 \Rightarrow \lambda_2 Q_u^S=0$, (5)$\lambda_1 \geq 0$, (6)$\lambda_2 \geq 0$, (7)$Q_n^S(P_n^S,Q_u^S)-Q_u^S \geq 0$, and (8)$Q_u^S \geq 0$. We also incorporate following conditions for the feasibility of the solution: (i) $1 > f_u > 0$, (ii) $1 > \delta > 0$, and (iii) $\mathbb{C} \geq 0$. The analysis identifies four candidate solutions:

Solution 1 ($Q_n^S(P_n^S,Q_u^S)=Q_u^S=0$): We solve $\lambda_1 \geq 0$, $\lambda_2 \geq 0$, $\frac{\partial\mathcal{L}}{\partial P_n^S}=0$, and $\frac{\partial\mathcal{L}}{\partial Q_u^S}=0$ simultaneously and get a condition $f_u \geq \frac{1+\delta-\mathbb{C}}{\delta}$. The solution has zero profit and therefore we ignore it.

Solution 2 ($Q_n^S(P_n^S,Q_u^S)>Q_u^S=0$): $\lambda_1=0$ and $\lambda_2 \geq 0$. Additionally, $\frac{\partial\mathcal{L}}{\partial P_n^S}=0$ and $\frac{\partial\mathcal{L}}{\partial Q_u^S}=0$. We solve them simultaneously and get $\lambda_2=\frac{(1-f_u)\delta(-1+(1-f_u)\delta+2\mathbb{C})}{1+3(1-f_u)\delta}$ and following conditions: (i) $f_u \leq \frac{2\mathbb{C}-1+\delta}{\delta}$ when $\mathbb{C}<\frac{2}{3}$ and (ii) $f_u<\frac{1+\delta-\mathbb{C}}{\delta}$ when $\mathbb{C} \geq \frac{2}{3}$. We have $P_n^{S*}=\frac{(1+(1-f_u)\delta+\mathbb{C})}{2}$. In addition, $Q_n^{S*}=\frac{1+(1-f_u)\delta-\mathbb{C}}{2(1+3(1-f_u)\delta)}$, $P_u^{S*}=\frac{(1-f_u)\delta(2(1-f_u)\delta+\mathbb{C})}{1+3(1-f_u)\delta}$, and $\Pi^{S*}=\frac{(1+(1-f_u)\delta-\mathbb{C})^2}{4(1+3\delta(1-f_u))}$.

Solution 3 ($Q_n^S(P_n^S,Q_u^S)>Q_u^S>0$): We solve $\lambda_1=0$, $\lambda_2=0$, $\frac{\partial\mathcal{L}}{\partial P_n^S}=0$, and $\frac{\partial\mathcal{L}}{\partial Q_u^S}=0$ simultaneously and get $\frac{2\mathbb{C}-1+\delta}{\delta}<f_u<\frac{1+\delta-\mathbb{C}}{\delta}$ when $\mathbb{C}<\frac{2}{3}$. We have $P_n^{S*}=\frac{(1+(1-f_u)\delta+\mathbb{C})}{2}$ and $Q_u^{S*}=\frac{1-(1-f_u)\delta-2\mathbb{C}}{2(1-(1-f_u)\delta)}$. In addition, $Q_n^{S*}=\frac{1-(1-f_u)\delta-\mathbb{C}}{2(1-(1-f_u)\delta)}$, $P_u^{S*}=\frac{\delta(1-f_u)}{2}$, and $\Pi^{S*}=\frac{1-(1-f_u)\delta+\mathbb{C}^2-2\mathbb{C}(1-(1-f_u)\delta)}{4-4\delta(1-f_u)}$.

Solution 4 ($Q_n^S(P_n^S,Q_u^S)=Q_u^S>0$): We solve $\lambda_1 \geq 0$, $\lambda_2=0$, $\frac{\partial\mathcal{L}}{\partial P_n^S}=0$, and $\frac{\partial\mathcal{L}}{\partial Q_u^S}=0$ simultaneously and find $\lambda_1=-(1-f_u)\delta\mathbb{C}$ and a infeasible condition $\mathbb{C} \leq 0$. Therefore, we rule out this casesolution.

The Hessian matrix of the producer's problem if it offers long warranties is $\begin{pmatrix} -\frac{2}{1+3\delta} & 0 \\ 0 & -\frac{2(1-\delta)\delta}{1+3\delta} \end{pmatrix}$. The first principle minor, $-\frac{2}{1+3\delta}$, is negative and the second principle minor, $\frac{4\delta(1-\delta)}{(1+3\delta)^2}$, is positive when $0<\delta<1$. Therefore, the problem is concave with respect to the producer's decision variables. The KKT Lagrangian equation is $\mathcal{L}=\Pi^L+\lambda_1(Q_n^L(P_n^L,Q_u^L)-Q_u^L)+\lambda_2(Q_u^L)$. The KKT conditions are: (1)$\frac{\partial\mathcal{L}}{\partial P_n^L}=0$, (2)$\frac{\partial\mathcal{L}}{\partial Q_u^L}=0$, (3)$\lambda_1(\frac{\partial\mathcal{L}}{\partial\lambda_1})=0 \Rightarrow \lambda_1(Q_n^L-Q_u^L)=0$, (4)$\lambda_2(\frac{\partial\mathcal{L}}{\partial\lambda_2})=0 \Rightarrow \lambda_2 Q_u^L=0$, (5)$\lambda_1 \geq 0$, (6)$\lambda_2 \geq 0$, (7)$Q_n^L(P_n^L,Q_u^L)-Q_u^L \geq 0$, and (8)$Q_u^L \geq 0$. Additional conditions are: (i) $1>f_u>0$, (ii) $1>\delta>0$, (iii) $\mathbb{C} \geq 0$, and (iv) $C_w \geq 0$. The analysis also identifies four candidate solutions:

Solution 1 ($Q_n^L(P_n^L, Q_u^L) > Q_u^L = 0$): We solve $\lambda_1 \geq 0$, $\lambda_2 \geq 0$, $\frac{\partial \mathcal{L}}{\partial P_n^L} = 0$, and $\frac{\partial \mathcal{L}}{\partial Q_u^L} = 0$ simultaneously and get $f_u \geq \frac{1+\delta-\mathbb{C}}{C_w}$ when $\mathbb{C} \geq 1$. We ignore this zero-profit solution.

Solution 2: ($Q_n^L(P_n^L, Q_u^L) > Q_u^L = 0$): We solve $\lambda_1 = 0$, $\lambda_2 \geq 0$, $\frac{\partial \mathcal{L}}{\partial P_n^L} = 0$, and $\frac{\partial \mathcal{L}}{\partial Q_u^L} = 0$ simultaneously and get $\lambda_2 = \frac{\delta(2\mathbb{C}-(1-\delta))-(1+\delta)f_u C_w}{1+3\delta}$ and following conditions: (i) $f_u < \frac{1+\delta-\mathbb{C}}{C_w}$ when $\mathbb{C} \geq 1$ and (ii) $f_u < \frac{\delta(2\mathbb{C}-1+\delta)}{(1+\delta)C_w}$ when $\mathbb{C} < 1$. We have $P_n^{L*} = \frac{(1+\delta+\mathbb{C}+f_u C_w)}{2}$. In addition, $Q_n^{L*} = \frac{1+\delta-\mathbb{C}-f_u C_w}{2(1+3\delta)}$, $P_u^{L*} = \frac{\delta(2\delta+\mathbb{C}+f_u C_w)}{1+3\delta}$, and $\Pi^{L*} = \frac{(1+\delta-\mathbb{C}-f_u C_w)^2}{4(1+3\delta)}$.

Solution 3 ($Q_n^L(P_n^L, Q_u^L) > Q_u^L > 0$): We have $\lambda_1 = 0$, $\lambda_2 = 0$, $\frac{\partial \mathcal{L}}{\partial P_n^L} = 0$, and $\frac{\partial \mathcal{L}}{\partial Q_u^L} = 0$, and get $\frac{\delta(2\mathbb{C}-1+\delta)}{(1+\delta)C_w} \leq f_u < \frac{\delta\mathbb{C}}{C_w}$ when $\mathbb{C} < 1$. We have $P_n^{L*} = \frac{(1+\delta+\mathbb{C}+f_u C_w)}{2}$ and $Q_u^{L*} = \frac{(1-\delta-2\mathbb{C})\delta+(1+\delta)f_u C_w}{2(1-\delta)\delta}$. In addition, $Q_n^{L*} = \frac{1-\delta-\mathbb{C}+f_u C_w}{2(1-\delta)}$, $P_u^{L*} = \frac{(\delta+f_u C_w)}{2}$, and $\Pi^{L*} = \frac{(1-\delta)\delta+\delta\mathbb{C}^2-2(1-\delta)\delta\mathbb{C}+f_u^2 C_r^2-2f_u\delta\mathbb{C}C_w}{4(1-\delta)\delta}$.

Solution 4 ($Q_n^L(P_n^L, Q_u^L) = Q_u^L > 0$): We solve $\lambda_1 \geq 0$, $\lambda_2 = 0$, $\frac{\partial \mathcal{L}}{\partial P_n^L} = 0$, and $\frac{\partial \mathcal{L}}{\partial Q_u^L} = 0$, and get $\lambda_1 = f_u C_w - \delta\mathbb{C}$ and $f_u \geq \frac{\delta\mathbb{C}}{C_w}$ when $\mathbb{C} < 1$. We have $P_n^{L*} = \frac{(1+\delta)(1+\mathbb{C})}{2}$ and $Q_u^{L*} = \frac{(1-\mathbb{C})}{2} = Q_n^{L*}$. In addition, $P_u^{L*} = \frac{\delta(1+\mathbb{C})}{2}$, and $\Pi^{L*} = \frac{(1-\mathbb{C})^2}{4}$. Summarizing all above, we have Proposition 3.2.

B.3 Proof of Corollary 3.3

We refer to Δ_{NN} as the difference in the optimal profits when the buy-back policies are suboptimal. $\Delta_{NN} = \Pi^L - \Pi^S$. If $\Delta_{NN} > 0$ under a given parameter set $\{\mathbb{C}, C_w, \delta, f_u\}$, the producer should offer long warranties and then price its products accordingly. $\Delta_{NN}(f_u) = 0$ has three roots, 0 and $\frac{-6\mathbb{C}\delta C_w+6\delta^2 C_w+3\delta C_w^2+6\delta C_w+C_w^2-3\delta^3-\delta^2 \pm (\delta-C_w)\sqrt{(1+3\delta)[(1+3\delta)\delta^2+2\delta C_w(6\mathbb{C}-3\delta-5)+(1+3\delta)C_w^2]}}{6\delta C_w^2}$. We denote the two non-zero roots of $\Delta_{NN}(f_u) = 0$ as f'_{NN} and f''_{NN}, $f'_{NN} \leq f''_{NN}$. In addition, $\Delta_{NN}(f_u)$ is indeterminate at $f_u = 1 + \frac{1}{3\delta}$, which is greater than 1 and can be ignored. Let $C_r < \delta$ and $\mathbb{C} < 1$, which implies $\overline{f_{NN}} = \frac{2\mathbb{C}-1+\delta}{\delta}$. We describe the characteristics of $\Delta_{NN}(f_u)$ in following cases:

(i) $f'_{NN}\&f''_{NN} \notin \mathbb{R}$, $f'_{NN} > \min[1, \overline{f_{NN}}]$, or $f''_{NN} < 0$, $\Delta_{NN}(f_u) < 0$ when $f_u \in (0, 1)$;

(ii) $f'_{NN} < 0 < f''_{NN} < \min[1, \overline{f_{NN}}]$: $\Delta_{NN}(f_u) > 0$ when $0 < f_u < f''_{NN}$ and $\Delta_{NN}(f) < 0$ when $f''_{NN} < f_u < \min[1, \overline{f_{NN}}]$;

(iii) $0 < f'_{NN} < f''_{NN} < \min[1, \overline{f_{NN}}]$: $\Delta_{NN}(f_u) < 0$ when $0 < f_u < f'_{NN}$ and when $f''_{NN} < f_u < \min[1, \overline{f_{NN}}]$. $\Delta_{NN}(f_u) > 0$ when $f'_{NN} < f_u < f''_{NN}$;

(iv) $0 < f'_{NN} < \min[1, \overline{f_{NN}}] < f''_{NN}$: $\Delta_{NN}(f_u) < 0$ when $0 < f_u < f'_{NN}$ and $\Delta_{NN}(f_u) > 0$ when $f'_{NN} < f_u < \min[1, \overline{f_{NN}}]$;

(v) $f'_{NN} < 0 < \min[1, \overline{f_{NN}}] < f''_{NN}$: $\Delta_{NN}(f_u) > 0$ when $f_u \in (0, 1)$.

When $C_w > \delta$ and $\mathbb{C} < 1$, $f'_{NN} > \min[1, \overline{f_{NN}}]$ always. When $C_w > \delta$ and $\mathbb{C} > 1$, $f'_{NN} > \frac{1+\delta-\mathbb{C}}{\frac{1+\delta}{\delta}C_w}$ always. When $C_w < \delta$ and $\mathbb{C} > 1$, we find $f'_{NN} > \frac{1+\delta-\mathbb{C}}{\delta}$ always. All imply that only case (i) exists. We then examine the cases and their conditions when $C_w < \delta$ and $\mathbb{C} < 1$. We denote $\frac{2}{3} - \frac{(3\delta+1)(\delta-C_w)^2}{12\delta C_w}$ as $s1_{NN}(\delta, C_w)$, $\frac{2(1+3\delta)C_w+\delta(1-3\delta)}{3\delta}$ as $s2_{NN}(\delta, C_w)$, and $-\frac{2\left(-2(\delta+1)\delta C_w+(\delta-1)C_w^2+\delta^3\right)}{(2C_w+\delta)^2}$ when $C_w \leq \frac{\delta^2}{\delta+1}$ and $-\frac{\left(\delta^2-7\delta-2\right)\delta C_w-\left(2\delta^2+3\delta+1\right)C_w^2+(\delta+1)(\delta-C_w)\sqrt{-(5\delta+1)\delta^2 C_w+(2\delta-}}{3\delta(3\delta+1)C_w}$ when $C_w > \frac{\delta^2}{\delta+1}$ as $s3_{NN}(\delta, C_w)$. $s2_{NN}(\delta, C_w) \geq s1_{NN}(\delta, C_w)$ and intersects with $s1_{NN}(\delta, C_w)$ once only at $C_w = \frac{\delta}{3}$. $s3_{NN}(\delta, C_w) \geq s1_{NN}(\delta, C_w)$ and intersects with $s1_{NN}(\delta, C_w)$ once only at $C_w = \frac{\delta(3\delta-1)+2\sqrt{\delta^2((\delta-1)\delta+1)}}{3+5\delta}$. In addition, $\frac{\delta(3\delta-1)+2\sqrt{\delta^2((\delta-1)\delta+1)}}{3+5\delta} > \frac{\delta}{3}$ when $\delta > 0$.

The conditions are as following:

(i) $f'_{NN}\&f''_{NN} \notin \mathbb{R}$ when $\mathbb{C} < s1_{NN}(\delta, C_w)$. To have $f''_{NN} < 0$, $s1_{NN}(\delta, C_w) < \mathbb{C} < s2_{NN}(\delta, C_w)$ and $C_w \leq \frac{\delta}{3}$. To have $f'_{NN} > \min[1, \overline{f_{NN}}]$, $s1_{NN}(\delta, C_w) < \mathbb{C} < s3_{NN}(\delta, C_w)$ and $C_w \geq \frac{2\sqrt{\delta^2((\delta-1)\delta+1)}+\delta(3\delta-1)}{5\delta+3}$;

(ii) To have $f'_{NN} < 0 < f''_{NN} < \min[1, \overline{f_{NN}}]$, $s2_{NN}(\delta, C_w) < \mathbb{C} < s3_{NN}(\delta, C_w)$;

(iii) To have $0 < f'_{NN} < f''_{NN} < \min[1, \overline{f_{NN}}]$;, $s1_{NN}(\delta, C_w) < \mathbb{C} < \min[s2_{NN}(\delta, C_w), s3_{NN}(\delta, C_w)]$;

(iv) To have $0 < f'_{NN} < \min[1, \overline{f_{NN}}] < f''_{NN}$, $s3_{NN}(\delta, C_w) < \mathbb{C} < s2_{NN}(\delta, C_w)$;

(v) To have $f'_{NN} < 0 < \min[1, \overline{f_{NN}}] < f''_{NN}$, $\mathbb{C} > \max[s2_{NN}(\delta, C_w), s3_{NN}(\delta, C_w)]$.

We summarize the above in Corollary 3.3 and illustrate case (iii) in Figure 3.4.

B.4 Sub-optimality of the Full Buy-back Policy

We can straightforwardly show that profits in the full buy-back policy when the producer offers long warranties equals profits in the partial buy-back policy when the producer offers short warranties with $\delta \to 0$. In addition, profits in the parital buy-back policy and the no buy-back policy increase in δ always, which implies that profits in the full buy-back policy when the producer offers long warranties are always dominated by the optimal profits when the producer offers short warranties.

B.5 Proof of Corollary 3.4

We also refer to Δ_{PP} as the difference in the optimal profits when the partial buy-back policy is optimal. $\Delta_{PP}(f_u) = 0$ also has three roots, 0 and $\frac{2\mathbb{C}\delta^2-(1-\delta)C_w \pm \sqrt{(1-\delta)(4\mathbb{C}\delta^2 C_w+(1-\delta)C_w^2-4\mathbb{C}^2\delta^3)}}{2\delta C_w}$. We denote the two non-zero roots of $\Delta_{PP}(f_u) = 0$ as f'_{PP} and f''_{PP}, $f'_{PP} \leq f''_{PP}$. In addition, $\Delta_{PP}(f_u)$ is indeterminate when $f_u = 1 - \frac{1}{\delta}$, which is negative and can be ignored. We describe the characteristics of $\Delta_{PP}(f_u)$ in following cases:

(i) $f'_{PP} \& f''_{PP} \notin \mathbb{R}$, $f'_{PP} > \min[\overline{\overline{f^L}}, 1]$, or $f''_{PP} < \max[0, \underline{f_{PP}}]$: $\Delta_{PP}(f_u) > 0$ when $f_u \in (0,1)$;

(ii) $f'_{PP} < \max[0, \underline{f_{PP}}] < f''_{PP} < \min[\overline{\overline{f^L}}, 1]$: $\Delta_{PP}(f_u) < 0$ when $\max[0, \underline{f_{PP}}] < f_u < f''_{PP}$ and $\Delta_{PP}(f_u) > 0$ when $f''_{PP} < f_u \leq \min[\overline{\overline{f^L}}, 1]$;

(iii) $\max[0, \underline{f_{PP}}] < f'_{PP} < f''_{PP} < \min[\overline{\overline{f^L}}, 1]]$: $\Delta_{PP}(f_u) > 0$ when $\max[0, \underline{f_{PP}}] < f_u < f'_{PP}$ and when $f''_{PP} < f_u < \min[\overline{\overline{f^L}}, 1]$. $\Delta_{PP}(f_u) < 0$ when $f'_{PP} < f_u < f''_{PP}$;

(iv) $\max[0, \underline{f_{PP}}] < f'_{PP} < \min[\overline{\overline{f^L}}, 1] < f''_{PP}$: $\Delta_{PP}(f_u) > 0$ when $\max[0, \underline{f_{PP}}] < f_u < f'_{PP}$ and $\Delta_{PP}(f_u) < 0$ when $f'_{PP} \leq f_u < \min[\overline{\overline{f^L}}, 1]$;

(v) $f'_{PP} < \max[0, \underline{f_{PP}}] < \min[\overline{\overline{f^L}}, 1] < f''_{PP}$: $\Delta_{PP}(f_u) < 0$ when $f_u \in (0,1)$.

When $\underline{f_{PP}} < 1$ and $\overline{\overline{f^L}} > 1$, $\mathbb{C} < \frac{1}{2}$, $C_w < \frac{\delta}{2}$, and $f''_{PP} < 1$; we have case (i), (ii), and (iii). Otherwise, when $\underline{f_{PP}} < 1$ and $\overline{\overline{f^L}} < 1$, $f''_{PP} > 1$; we then have case (i), (iv), and (v). We examine the conditions of these cases and denote $\frac{\left(\frac{1}{\sqrt{\delta}}+1\right)C_w}{2\delta}$ as $s1_{PP}(\delta, C_w)$, $\frac{2(1-\delta)C_w}{\delta}$ when $C_w < \frac{\delta}{4}$, $\frac{\sqrt{\delta(\delta+1)^2(C_w(\delta C_w-2\delta^2+\delta+1)+(\delta-1)\delta^2)}+(\delta+1)\delta C_w-\delta^3+\delta^2}{\delta(3\delta+1)}$ when $\frac{\delta}{4} < C_w < \frac{\delta^2}{\delta+1}$, and $\frac{2(1-\delta)C_w^2}{4C_w(C_w-\delta^2)+\delta^3}$ when $\frac{\delta^2}{\delta+1} < C_w < \frac{\delta}{2}$ as $s2_{PP}(\delta, C_w)$, and $\frac{C_w}{\delta}$ as $s3_{PP}(\delta, C_w)$. $s2_{PP}(\delta, C_w) \leq s1_{PP}(\delta, C_w)$, intersects with $s1_{PP}(\delta, C_w)$ once only at $C_w = \frac{1}{2\left(\frac{1}{\delta}\right)^{3/2}}$, and ends by intersecting with $s3_{PP}(\delta, C_w)$ at $C_w = \frac{\delta}{2}$. We further summarize the conditions of these cases as following:

(i) $f'_{PP}\&f''_{PP} \notin \mathbb{R}$ when $\mathbb{C} > s1_{PP}(\delta, C_w)$. To have $f''_{PP} < \max[0, \underline{f_{PP}}]$, $s2_{PP}(\delta, C_w) < \mathbb{C} < s1_{PP}(\delta, C_w)$ when $C_w > \frac{1}{2\left(\frac{1}{\delta}\right)^{3/2}}$. In addition, $f'_{PP} < \min[\overline{\overline{f^L}}, 1]$ always;

(ii) To have $f'_{PP} < \max[0, \underline{f_{PP}}] < f''_{PP} < 1$ (and $1 < \overline{\overline{f^L}}$), $s3_{PP}(\delta, C_w) < \mathbb{C} < s2_{PP}(\delta, C_w)$;

(iii) To have $\max[0, \underline{f_{PP}}] < f'_{PP} < f''_{PP} < 1$ (and $1 < \overline{\overline{f^L}}$), $\max[s2_{PP}(\delta, C_w), s3_{PP}(\delta, C_w)] < \mathbb{C} < s1_{PP}(\delta, C_w)$ when $C_w < \frac{1}{2\left(\frac{1}{\delta}\right)^{3/2}}$;

(iv) To have $\max[0, \underline{f_{PP}}] < f'_{PP} < \overline{\overline{f^L}} < f''_{PP}$ (and $\overline{\overline{f^L}} < 1$), $s2_{PP}(\delta, C_w) < \mathbb{C} < s3_{PP}(\delta, C_w)$;

(v) If $f'_{PP} < \max[0, \underline{f_{PP}}] < \overline{\overline{f^L}} < f''_{PP}$ (and $\overline{\overline{f^L}} < 1$), $\mathbb{C} < \min[s2_{PP}(\delta, C_w), s3_{PP}(\delta, C_w)]$.

We summarize the above in Corollary 3.4 and illustrate case (iii) in Figure 3.5.

APPENDIX C

TABLES OF RESULTS FOR ROBUSTNESS CHECKS IN CHAPTER 4

Table C.1: Un-weighted used-vehicle reliability

Variables	Model 1-1 $WarrantyLength\_NonPower$	Model 1-2 $WarrantLength\_Power$	Model 1-3 $BuyBack$	Model 1-4 $UsedTradeVolume$
$UnweightedUsedReliability\_NonPower$	1.024***			
	(0.311)			
$UnweightedUsedReliability\_NonPower^2$	0.263***			
	(0.093)			
$UnweightedUsedReliability\_Power$		4.210***		
		(1.275)		
$UnweightedUsedReliability\_Power^2$		3.973**		
		(1.586)		
$UnweightedUsedReliability$			-0.370***	0.975***
			(0.087)	(0.237)
Lagged $UsedTradeVolume$				-0.099
				(0.060)
Observations	198	198	177	158
χ^2	43.46	42.36	26.13	
R^2				0.2298

Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.10.

Table C.2: Alternative used-vehicle reliability

Variables	Model 2-1 $WarrantyLength\_NonPower$	Model 2-2 $WarrantyLength\_Power$	Model 2-3 $Buyback$	Model 2-4 $BuyBack$	Model 2-5 $UsedTradeVolume$	Model 2-6 $UsedTradeVolume$
$UsedReliability$	1.011***	0.485				
	(0.203)	(0.610)				
$UsedReliability^2$	0.203***	0.048				
	(0.048)	(0.162)				
$UsedReliability\_NonPower$			-0.308***		0.818***	
			(0.105)		(0.240)	
$UsedReliability\_Power$				-1.594***		2.228**
				(0.315)		(0.732)
Lagged $UsedTradeVolume$					-0.116	-0.101
					(0.083)	(0.067)
Observations	198	198	177	177	158	158
χ^2	56.87	21.43	20.41	35.75		
R^2					0.1509	0.1860

Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.10.

Table C.3: Additional tests for secondary market trade volume

Variables	Model 3-1 VOT	Model 3-2 VOT'	Model 3-3 $UsedTradeVolume$
$UsedReliability$	0.632***	0.692***	0.641***
	(0.145)	(0.163)	(0.167)
Lagged VOT	-0.222***		
	(0.063)		
Lagged VOT'		-0.202***	
		(0.00)	
Lagged $UsedTradeVolume$			0.614***
			(0.097)
Observations	160	160	158
R^2	0.2218	0.2135	
χ^2			4179

Standard errors in parentheses: *** p<0.01, ** p<0.05, * p<0.10

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VITA

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